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GEOLOGY FOR PLANNING IN SONOMA COUNTY

1980

CALIFORNIA DIVISION OF MINES AND GEOLOGY

SPECIAL REPORT 120

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Special Report 120

GEOLOGY FOR PLANNING IN SONOMA COUNTY

by

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CALIFORNIA DIVISION OF MINES AND GEOLOGY
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including

"SEISMICITY, GROUND SHAKING, AND LIQUEFACTION POTENTIAL"

by

Roger W. Greensfelder, Seismologist

1980

PREPARED IN COOPERATION WITH THE SONOMA COUNTY PLANNING DEPARTMENT

CONTENTS

PREFACE v
SUMMARY v
  Seismic hazards v
  Non–seismic hazards vi
RECOMMENDATIONS vi
RECOMMENDATIONS CONCERNING SEISMIC SAFETY ENGINEERING By Roger W. Greensfelder vii
INTRODUCTION 1
  Scope 1
  Methods of investigation 1
  Capabilities of this report 1
    Uses 1
    Limitations 2
  Acknowledgments 3
GEOLOGIC SETTING OF SONOMA COUNTY 3
SEISMICITY, GROUND SHAKING, AND LIQUEFACTION POTENTIAL By Roger W. Greensfelder 5
  General considerations 5
  Seismicity 7
    History of damaging earthquakes 7
      1906 earthquake 7
      1969 Santa Rosa earthquakes 8
      Intensity recurrence 9
    Earthquake magnitude versus frequency of occurrence 9
    Epicenter distribution and active faults 9
  Seismically induced ground motions 12
      Maximum shaking in rock 12
        Maximum credible rock acceleration 12
        Maximum probable rock acceleration 13
      General characteristics of ground shaking 13
        Estimation of alluvial thickness 14
      Liquefaction and its effects 14
FAULT RUPTURE 15
  Potentially active faults 17
    Burdell Mountain fault 17
    Chianti fault 17
    Healdsburg fault 17
    Maacama fault 19
    Rodgers Creek fault 19
    San Andreas fault 19
    Tolay fault 19
  Possibly active faults 19
    Black Mountain fault 19
    Dianna Rock fault 19
    Tombs Creek fault 19
    Mt. Jackson fault 20
    Other possibly active faults 20
TSUNAMI HAZARD 20
LANDSLIDES AND SLOPE STABILITY 20
  Recognition of landslides 20
  Landslide types in Sonoma County 20
  Causes of landslides 22
    Geologic materials 22
    Natural processes 22
      Earthquakes 22
    Man's activities 23
    Slope inclination 23

Time 23
Proximate and contributing causes 24
Slope stability evaluation 24
Categories of stability 24
GLOSSARY OF SELECTED GEOLOGIC TERMS 27
REFERENCES CITED 29

ILLUSTRATIONS

Plate 1A. Relative hazard from seismic shaking and tsunami hazards in northern Sonoma County .. Pocket
Plate 1B. Relative hazard from seismic shaking and tsunami hazards in southern Sonoma County .. Pocket
Plate 2A. Landslides and relative slope stability – northern Sonoma County .... Pocket
Plate 2B. Landslides and relative slope stability – southern Sonoma County .... Pocket
Plate 3A. Geologic map exclusive of landslides – northern Sonoma County .... Pocket
Plate 3B. Geologic map exclusive of landslides – southern Sonoma County .... Pocket
Plate 4. Earthquake epicenters .... Pocket
Plate 5. Crustal movement investigations .... Pocket

Figure 1. Location map 2
Figure 2. Intensity recurrence: Santa Rosa Valley region 10
Figure 3. Magnitude vs. frequency of occurrence for the Sonoma County region 11
Figure 4. Schematic representation of relationship between geology, response spectra, building height, and potential damage in a strong local earthquake 13
Figure 5. Types of fault movement 16
Figure 6. Block diagram showing landforms produced along recently active faults (modified from Clark, 1971) 18
Figure 7. Drawing showing some features of an idealized landslide 21

Table 1. Geologic time scale v
Table 2. Modified Mercalli intensity scale of 1931 (1956 version) 6
Table 3. History of damaging earthquakes in Sonoma County 7
Table 4. Earthquake recurrence intervals for the Sonoma County region 12

PREFACE

From the birth of planet Earth and the solar system 4.6 billion years ago to the 20th century, the world has been in a constant state of change. Geologic change has set the stage and created the physical environment in which man has evolved and in which he must now live.

In man's short life span, most geologic changes are imperceptible: the slow upward folding of a mountain range, the snail-paced *spreading** of the ocean floor, the microscopic chemical weathering of a feldspar crystal to clay, and the gradual downcutting of a mountain by a stream. Other geologic changes are more perceptible to us: the changes in shape of a meandering stream channel, the metamorphosis of a mountain pond to a bog and finally a meadow, the gradual loss of an ocean sand beach to the waves, and the tearing and cracking of a paved road yielding to the forces of *fault creep*. Frequently, however, the slow march of geologic time and change is punctuated by more rapid and violent actions. An earthquake, a landslide, a volcanic eruption, or the once in a century inundation of a vast flood plain — all bring drastic changes to the face of the earth (the environment) in a matter of minutes or hours.

Whether the change is gradual or rapid, the result is liable to be a disruption of the environment in which man lives or works. Most geologic hazards cannot be removed and should not be ignored. It is important, then, to identify and plan for these changes or hazards so that man may continue his existence with as little interruption as possible. It is toward this end – the identification of geologic hazards for planning purposes – that this report is addressed.

From Precambrian to Holocene, the natural forces of time and change have marched steadily onward (table 1). But now, in Holocene time, man has coupled additional energy to natural processes. Often by design, sometimes unwittingly, man accelerates geologic change, and the results are to his disadvantage. *Saltwater intrusion* caused by excessive withdrawal from freshwater coastal *aquifers,* landslides caused by oversteepened road cuts, rapid stream erosion below reservoirs, and earthquakes induced by fluid injection wells are all predictable and preventable.

SUMMARY

Seismic Hazards

The geology map exclusive of landslides (plates 3A and 3B) identifies seven potentially active faults in Sonoma County. The San Andreas fault created offsets of as much as 12 feet in Sonoma County in 1906, and it is believed that the other seven potentially active faults are also capable of damaging movement. Such movement alone, whether it be rapid slip or slow creep, is capable of damaging the sturdiest structures. The map also shows "possibly active faults" which require further study to ascertain their degree of activity.

Table 1. Geologic time scale.

Era	*Period*	*Epoch*	*Beginning of Interval. Approximate number of years before present.*	*Approximate length of interval in years.*
Cenozoic	Quaternary	Holocene	10,000	10,000
		Pleistocene	1.8 million	1.8 million
	Tertiary	Pliocene	7 million	5.2 million
		Miocene	26 million	19 million
		Oligocene	38 million	13 million
		Eocene	54 million	16 million
		Paleocene	65 million	11 million
Mesozoic	Cretaceous		136 million	71 million
	Jurassic		195 million	59 million
	Triassic		225 million	30 million
Paleozoic			570 million	345 million

Adapted from "Major Stratigraphic and Time Divisions", Geologic Names Committee, U.S. Geological Survey, 1972.

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* Important terms not defined in technical sections are italicized the first time they appear and are defined in the glossary.

Sonoma County can be affected by earthquake shaking caused by faulting within its borders and from outside the County. Analysis of regional seismicity indicates that potentially damaging ground shaking may be expected to recur on an average of once every 20 to 30 years in Sonoma County. A major earthquake somewhere on the San Andreas fault is expected to recur every 50 to 200 years. The 1906 earthquake, with its *epicenter* on the San Andreas fault, caused relatively more direct damage in Santa Rosa and Sebastopol than it did in San Francisco, which is much closer. This damage was not a result of fault rupture, but rather of the transmission of the fault energy into vibratory motion or ground shaking.

Ground shaking, liquefaction, *differential settlement, lurch cracking,* and landsliding are all effects of earthquake faulting. The distribution of these effects and their potential for damage are determined by the epicenter, magnitude, and frequency of the earthquake; the types of bedrock through which the energy is transmitted; the response of unconsolidated earth materials; and the response of man–made structures to resultant ground motion. Plates 1A and 1B show the relative hazard from seismic shaking, based on data which indicate the general degree of consolidation of materials.

A tsunami (or seismic sea wave) is a real, but minor, threat to lives and property in Sonoma County. Plates 1A and 1B show the probable inundation of the Sonoma coast and tidal lands that could be caused by a 200–year tsunami, assuming a maximum wave run–up of 20 feet above sea level along the coast and considerably less for tidal lands bordering San Pablo Bay (Ritter and Dupre, 1972).

Non–Seismic Hazards

Slope stability problems are widespread throughout Sonoma County. The combination of seasonally high rainfall, steep slopes, and unstable bedrock result in the occurrence of landslides in nearly all upland areas in the County. Some bedrock units are more stable than others, but it is impossible to find any unit totally free of landslide activity.

Although many of the landslides shown on the Landslides and Slope Stability Map (plates 2A and 2B) are ancient and may be stable under present climatic conditions, man's activity can reactivate them. Cuts and fills oversteepen slopes and increase loads, respectively, while lawn watering and septic tanks increase moisture. In addition to delineating landslides, Plates 2A and 2B show areas of relative stability as determined by an abundance of landslides, slope, and bedrock geology.

Accelerated water erosion occurs throughout the County in highland areas where thick soils or unconsolidated bedrock units are encountered. Along the Sonoma coast, sea cliff erosion is prevalent regardless of bedrock geology.

RECOMMENDATIONS

1. The County Engineering Advisory Committee should require a site geologic report prior to the approval of a final major subdivision map in areas designated as landslides, possible landslides, and areas C, B, and Bf on Plates 2A and 2B. Site geologic and soil investigations of potential earthquake–induced liquefaction also should be required for developments adjacent to the Russian River and other major waterways in A areas.

2. The Engineering Advisory Committee should require a reconnaissance–level geologic feasibility report as a condition for the approval of a tentative major subdivision map in areas designated as landslides, possible landslides, and C areas on Plates 2A and 2B.

3. The Engineering Advisory Committee should require site geologic reports prior to the validation of minor subdivisions in areas designated as landslides, possible landslides, or in C areas on Plates 2A and 2B.

4. The Chief Building Inspector should require a site geologic report as a condition for the issuance of a building permit in areas designated as landslides, possible landslides, or in C areas on Plates 2A and 2B. A geologic report should be required, at the discretion of the Chief Building Inspector, where local conditions indicate that geologic hazards may exist in B and Bf areas. Reference should be made to Division of Mines and Geology reports on local areas of the County for more detailed information.

5. The Chief Building Inspector should require a geologic report, in conformance with Chapter 70 of the Uniform Building Code, as a condition for the issuance of a grading permit in areas designated as landslides, possible landslides, or in C areas on Plates 2A and 2B. A geologic report should be required, at the discretion of the Chief Building Inspector, where local conditions indicate geologic hazards may exist in B and Bf areas. Reference should be made to Division of Mines and Geology reports on local areas of the County for more detailed information.

6. Younger bay mud shown on Plate 1B should be considered unsuitable for development unless site geologic and soils investigations and engineering designs demonstrate that proposed structures will not sustain undue damage from soil movement during major earthquakes.

7. Possibly active faults shown on Plates 3A and 3B should be investigated to more fully ascertain their degree of hazard. In the absence of scientific studies, approval of development proposed within one–eighth of a mile of these faults should require geologic reports which conform to the stipulations of the Alquist–Priolo Special Studies Zones Act.

8. All geologic and environmental impact reports reviewed by the County should address specifically the hazards indicated on the maps accompanying this report, such as landsliding, ground shaking, and active faulting.

9. The County should require geologic reports in conformance with the Alquist–Priolo Act for potentially active faults shown on Plates 3A and 3B which have not been zoned for special studies by the State Geologist.

10. Geologic reports for the planning of engineered developments should be prepared by a geologist registered in California and certified in engineering geology.

11. All geologic reports submitted should be reviewed for adequacy on behalf of the County by a geologist registered in California and certified in engineering geology.

12. The County should employ a staff engineering geologist to administer geologic study requirements, review submitted geologic reports, and provide expertise to County government as needed.

13. The County should support continuing public education on geologic hazards. The accompanying hazards maps should be posted prominently near public inquiries counters. Interested citizens should be informed that professional geologists are available to perform required studies and that general geologic information is available from public agencies.

14. The accompanying maps should be revised to reflect new data as it becomes available from site investigations and scientific research.

15. The County should continue to provide geologic hazards mapping of local areas to aid current planning and implementation of the General Plan.

RECOMMENDATIONS CONCERNING SEISMIC SAFETY ENGINEERING

by Roger W. Greensfelder

1. Determine an acceptable level of seismic risk. How many deaths and how much structural damage (dollar losses) can be tolerated? Once this has been established with public approval, various code revisions can be considered together in the context of reducing risk to a predetermined level. Because the greatest risks will occur in heavily populated areas, the County should work closely with the cities which will have jurisdiction over most of the population. Ideally, the County could coordinate the seismic risk reduction efforts of cooperating cities.

2. Determine which categories of structures need to be regulated more restrictively than at present (e.g. by use of the Uniform Building Code—UBC). Then, in consultation with structural engineers who are expert in dynamic analysis, decide to what extent a stiffening of the pseudo-static methods of the UBC should be relied upon, and where dynamic analysis should be required. Finally, and again in consultation with expert structural engineers and engineering geologists, the County would revise its building and grading codes.

3. If the County or a cooperating city decides to require dynamic analysis for high-rise buildings, it should also require analytical prediction of ground motion at the building site. This is a difficult problem requiring a great deal of data for solution. Therefore, in limited areas of expected high-rise development, it would be reasonable for local government to consider doing a ground-motion analysis which could be applied to the design of a number of buildings. The cost could be recovered by means of a special building permit surcharge.

Of all risk-reducing measures, building and grading code revision is the most difficult because it involves at least implicit prediction of ground motion and building response. Ideally, any code revisions should be based on a careful, thorough analysis of past building performance. This would be beyond the means of most counties; however, several organizations are involved in research to improve aseismic design and relevant building code provisions.

GEOLOGY FOR PLANNING IN SONOMA COUNTY

by M.E. Huffman and C.F. Armstrong*

INTRODUCTION

This study is the product of a cooperative agreement between the County of Sonoma and the California Division of Mines and Geology. It was undertaken to provide information needed by the County to fulfill the requirements of the State–mandated Seismic Safety and Safety Elements of the County General Plan. The information generated will contribute to the formulation of policies and regulatory procedures for public safety.

Scope

The Division gathered available data to provide overview and County–wide synthesis of geologic hazards information. Specific hazards were earthquake ground shaking and liquefaction potential, surface fault rupture, landslides and slope stability, and tsunamis. In large areas, the location and character of potentially active faults and landslides could not be delineated at the desired scale from published data. For these areas, therefore, aerial photographic interpretation supplemented by limited field checking was used to provide this information. The maps accompanying this report identify the location of hazards and designate several levels of hazards, thus providing a means for ascertaining levels of acceptable risk. Recommendations herein will assist the County in implementing measures to mitigate hazards where risks are unacceptable. Some geologic hazards data were found inadequate for this purpose, and further studies are recommended.

Methods of Investigation

Data were compiled on the 1:62,500 base map used by the County Advanced Planning Division for general planning. For purposes of compilation, the County was divided into two sectors of approximately equal areas; Huffman was assigned chief responsibility for the north half, and Armstrong for the south half. Greensfelder analyzed ground shaking and liquefaction potential based on information provided by Huffman, Armstrong, and Charles Bishop*. Historical seismicity and earthquake statistics were also analyzed.

Overlapping pairs of vertical 9 x 9–inch aerial photographic prints were examined with a stereoscope to provide interpretative data where none were available. Two sets of photographs were used: (1) Sonoma County 1:24,000 (approximate) scale prints (1971), and (2) U.S. Geological Survey 1:80,000 (approximate) scale prints (1970). A similar method was used by U.S. Geological Survey geologists to develop landslide data that was compiled on the maps.

Capabilities of This Report

USES

In conjunction with other planning factors, the maps and data may be used: (1) to implement General Plan goals and policies, (2) to derive alternative land–use plans, and (3) as a planning tool to conserve open space and natural resources. The maps, descriptions, and recommendations also will guide the preparation and review of environmental impact reports and site evaluations.

The accompanying maps identify areas where there are geologic hazards. This is the first step in attaining the General Plan goal of avoiding land uses which "threaten public safety and property value" (Sonoma County Planning Department, p. III–1).

Establishment of "policies and programs which provide for risk reduction", including those under "Recommendations" in this report, should be guided by information herein. Relative levels of hazard have been defined and mapped to permit assessment of relative risk. Mitigating measures may be applied where the level of risk exceeds that which the County deems acceptable.

The County can hold population densities and development to a minimum in areas of geologic hazard by: (1) adopting and enforcing appropriate zoning, (2) requiring rigorous, detailed geologic studies and applying their results, and (3) educating the public to avoid or mitigate extant hazards.

Land use plans, where developed at scales appropriate to the data herein, should use the geologic hazards information presented in this report. General Plan alternatives, formulated on a regional landscape unit basis, should be decided upon only after significant consideration is given to geologic factors. Population and dwelling unit densities, transportation nets, development costs, and desirable sites for residential, commercial, agricultural, and open space areas should all be selected with full knowledge of the kind and degree of geologic hazard that may be present.

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*Geologists, California Division of Mines and Geology.

Certain of the geologic risks are prohibitive to safe and economic land development and various forms of open space use are most appropriate. These open space areas may need to range in size from relatively narrow belts along active fault traces in developed areas to vast tracts mantled by active landslides, where all development should be avoided. They may be designated as a result of site geologic investigations, planning studies, assignment of low dwelling–unit densities in hazardous areas, or public recognition and avoidance of prohibitive hazards.

Reference to the accompanying maps, especially to Plates 3A and 3B, will show that on many hillside terrains severe hazards predominate and areas of safe development are restricted. In such terrains, lands which can be safely developed are a scarce resource which should be managed as such.

LIMITATIONS

Sources of uncertainty in the accuracy and completeness of the maps limit their usefulness for some purposes.

1) The maps were prepared by a synthesis of data derived from various geologists who worked at different times, in studies of varying intensities, technical approaches, and aims.
2) Many source data were obtained by aerial photographic interpretation without field verification.
3) The data were generalized and some details were omitted in order to prepare a uniform final product.

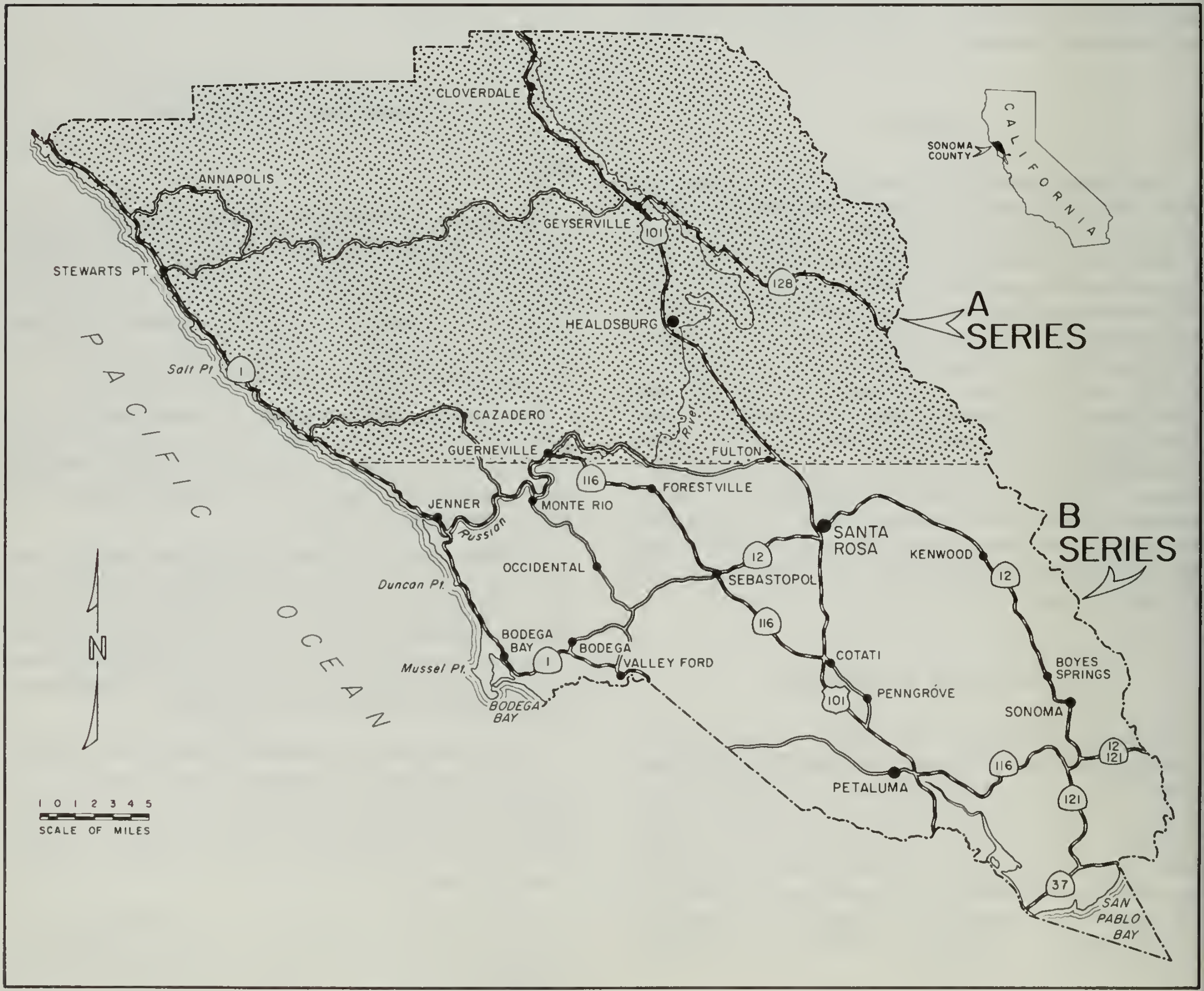


Figure 1. Location map

4) Geologic features are grouped under general headings and same features, such as landslides, may have highly variable characteristics and risk values when considered in detail.

For these reasons, use of the data for detailed planning at scales larger than these maps will lead to distortions and misrepresentation of fact. The error will become greater with greater disparity of scales, because the larger the scale, the greater the implication of high–level detailed investigation. If the data were to be enlarged and shown on maps with dwelling–unit density zones and ownership parcels, inaccuracies would almost surely lead to erroneous judgments affecting substantial interests. Therefore, such uses should be avoided. The information conveyed by the maps is inadequate for individual site evaluation, such as for a dwelling, subdivision development, road alignment, or dam. Determination of the suitability of a particular building site requires detailed investigation of the specific site and of the uses under consideration. Individual site investigation often includes detailed geologic mapping, *geophysical surveys,* drilling and trenching, soil sampling, and laboratory testing.

The maps and interpretations in this report should be modified to include any new facts and understanding that may develop from future site investigations, scientific studies, and other sources.

Acknowledgments

The information presented here is the product of the cumulative efforts of many workers, only some of whom can be acknowledged in the lists of sources and references.

The cooperation of the U.S. Geological Survey, which provided published and unpublished data, was very beneficial to this study. U.S.G.S. geologists, who provided unpublished landslide mapping for inclusion in the compilation, are cited in the list of references.

Donald A. Rodgers developed the computer program used in plotting the epicenter data on plate 4. Tousson R. Toppozada reviewed seismological sections of the report and contributed helpful suggestions. John H. Bennett provided the compilation of crustal strain measurement stations shown on Plate 5. Richard Knox plotted most of the geologic information shown on Plate 3A.

Sonoma County Advanced Planning Division staff, especially Paul T. Fenner and Steven Maki, contributed helpful discussions on form and content of this report.

GEOLOGIC SETTING OF SONOMA COUNTY

The geology of the California Coast Ranges is related in time and space by the concept of "plate tectonics". Modern geologic knowledge indicates that the earth's outer shell comprises several large plates which are in motion relative to one another and to the earth's core, and which are driven by deep–seated forces. The San Andreas fault, which extends more than 600 miles from northern California to the Salton Sea, is at the juncture of two such plates. The Pacific plate on the west of the fault is moving north with respect to the North American plate on the east. As a result, regional strain or deformation of the rocks increases with time until the rocks fracture periodically. These zones of fracture are the San Andreas fault and its related subordinate faults. When the fracturing and displacement of adjacent rock masses intersect the surface, surface fault rupture and slip occur. The vibrations radiated from such an event on the fault are felt as earthquake ground shaking. Aside from the San Andreas fault itself, the potentially active faults in Sonoma County (plates 3A and 3B) are subordinate members of the San Andreas system; the trend and mode of slip of each is identical to that of the master fault.

The San Andreas fault system has been the location of repeated horizontal movements for at least the past 25 million years (Dickinson and Grantz, 1968, p. 118). In that span of time, cumulative offsets have moved some points on the west side of the fault about 200 miles northwestward with respect to those on the east side (Addicott, 1968, p. 144), juxtaposing two widely different geologic provinces.

East of the San Andreas fault, "basement" bedrock is the Franciscan Group (plates 3A and 3B), which underlies an estimated 40–50 percent of Sonoma County. These rocks originated when the ancestral Pacific and North American plates collided during a time spanning probably 40 to 150 million years ago. As a result of this collision, the oceanic plate was slowly forced beneath the continental plate by slipping along a massive fault system. Downwarping of the ocean floor at the juncture created deep trenches, analogous to those existing at certain borders of the Pacific Ocean today in similar geologic environments. Sedimentary and volcanic rocks accumulated therein and were slowly thrust beneath the continental plate, along with the oceanic plate. Subsequent uplift has brought them to the surface where they are identified as rocks of the Franciscan Group. Serpentinite, which is widespread in the Franciscan Group, is a metamorphic rock derived from crystalline mantle material which underlies the crust of the earth. It was forced into the faults during deep thrusting of the Franciscan sediments. Rocks of the Great Valley Sequence represent remnants of the upper plate and are separated from the underlying Franciscan Group by thrust faults.

As a result of being thrust under in the massive ancient fault zone, the rocks of the Franciscan Group are highly sheared and fractured on every scale and, in many cases, are virtually shredded. Commonly, isolated knobs of resistant volcanic rock rise above a landscape underlain by sheared shale and sandstone. Landslides form abundantly on these pervasively weakened rocks, often blanketing the terrain with a slowly moving mantle. The Franciscan Group has long been notorious for its shattered rocks, high instability, and extensive landslides, and contributes greatly to these hazards in Sonoma County.

The stratigraphic record east of the San Andreas fault is broken. Rocks of Pliocene age (table 1) are the oldest that are abundantly deposited on the basement of the Franciscan Group. Noteworthy among these are the contemporaneous Merced Formation and Sonoma Group. The Merced Formation is dominantly a fairly uniform siltstone, deposited in a marine embayment which covered what is now southwestern Sonoma County. Marginal to this embayment, lava flows and vocalnic ash of the Sonoma Group were being erupted to the east. The Petrified Forest in eastern Sonoma County contains a flora including redwood trees and firs which were buried by volcanic ash during the later phases of Sonoma volcanism. Age of these rocks was determined, by measure of products of the decay of radioactive elements in them, to be 3.4 million years (Evernden and James, 1964). Toward the end of the epoch, structural deformation formed valleys and plains in the Sonoma Group terrain, and sand, silt and gravel of the *Plio–Pleistocene* Glen Ellen Formation were deposited in these basins by streams eroding the surrounding highlands.

During Pleistocene time, crustal deformation, mountain building, and erosion formed the landscape that has endured to the present day. Western Sonoma County has been uplifted and the Merced Formation tilted gently eastward. Higgins (1952) has theorized that the meandering western course of the Russian River developed as that stream followed the retreating Merced sea across the uplifted plain. The river carved a deep canyon into the mountain as uplift continued. Flights of marine *terraces* along the coast, those at higher elevations being increasingly older, record successive uplifts. The highest of these are nearly 1000 feet in elevation. The Glen Ellen Formation, Sonoma Group, and eastern Sonoma County rocks generally were more severely folded and faulted than the Merced Formation. The Sonoma–Kenwood Valley and other valleys reflect folding of these rocks.

The Mayacamas Mountains are a great, complexly fractured block uplifted along faults. Several of the potentially active faults in the County now manifesting horizontal movements apparently were the sites of significant vertical displacements during the early stages of development of the present topography. The hills formed on the Merced Formation in southwestern Sonoma County have less relief and far fewer landslides than the eastern hills underlain by the complexly faulted and heterogeneous Sonoma Group and Glen Ellen Formation. Differences in intensity of deformation and/or rock types are reflected in the difference in the number of landslides in the Merced Formation and the Sonoma Group.

During the Pleistocene Epoch, climatic changes accompanied several vast advances and retreats of glacial ice and oscillations of sea level. These climatic changes may have triggered the very large ancient landslides that are extensively distributed in the mountains of Sonoma County. The last retreat of the glaciers commenced about 20,000 years ago. Since then, sea level has risen 200 to 300 feet, inundating the areas of San Pablo and Bodega Bays, as well as other areas, and producing the tidal marshes and younger bay sediments ("bay mud" on plate 1). During late Quaternary time, sedimentation of the older valleys and plains created extensive deposits of Quaternary alluvium. Because of low elevation, loosely consolidated material, and high ground water levels, the younger bay sediments and Quaternary alluvium present a significantly higher risk from the hazards of earthquake ground shaking and liquefaction than adjacent bedrock areas.

Survey measurements and the record of earthquakes in Sonoma County indicate that the process of plate movement and strain build–up continues to this day. The annual heavy winter rains induce landslide movement and cause erosion in the mountain canyons. Some of the debris is deposited as sediment on the flood plains. These natural geologic forces produce fault rupture, earthquakes, landslides, and tsunamis, which are the geologic hazards to man's environment and his works addressed in this report.

SEISMICITY, GROUND SHAKING, AND LIQUEFACTION POTENTIAL

by Roger W. Greensfelder

General Considerations

Sonoma County, along with most other coastal areas of California, is threatened by intense earthquake hazards. State legislation aimed at mitigation of certain seismic risks was enacted in 1972 as the Alquist–Priolo Geologic Hazards Zones Act which required the State Geologist to delineate special studies zones along major active faults. The San Andreas fault has been zoned accordingly, and maps for Sonoma County have been distributed to the County Planning and Public Works Departments. The Hospital Safety Act (1972) sets rigid standards for earthquake–resistant design of hospitals. Similar standards for other emergency service structures were encompassed in other legislation (SB 1372 and SB 2149) that failed in 1974. Schools have been covered by the Field Act since 1933. Local governmental action is also warranted to reduce risk to life and property from geologic hazards.

However, the most important earthquake hazard, ground shaking, and its potential effect on most buildings, are not dealt with by State or local regulations other than the generally–adopted provisions of the Uniform Building Code. The "Urban Geology Master Plan for California" (Alfors and others, 1973, p. 4) indicates that projected losses for the period 1970–2000 are about 250 times greater from ground shaking than from fault displacement.

Local governments in California have adopted most provisions of the Uniform Building Code (UBC), including those dealing with earthquake–resistant design of buildings. Adequate enforcement of the UBC appears to be lacking in many local jurisdictions. The UBC's seismic requirements appear to have reduced risk to life to an acceptably low level in modern low–rise structures, although the benefits of further property damage risk reduction might warrant additional safety engineering measures. However, the effectiveness of the UBC to reduce life risk in high–rise structures remains to be tested adequately. Experience with modern high–rise buildings subjected to very strong ground shaking is quite limited. Damage to high, reinforced concrete buildings did occur in the 1964 Anchorage, 1967 Caracas, and 1971 San Fernando earthquakes. In Caracas, four 10–12 story, reinforced concrete apartment buildings collapsed, killing more than 200 persons. However, enforcement of building codes in Caracas was lacking. Steel frame buildings appear to be safer, due to their greater ability to absorb shaking energy without failure.

The UBC's earthquake–resistant design provisions are based on the "pseudostatic" method of analysis, wherein the dynamic response of a structure is treated in terms of supposedly equivalent static loads, deflections, and stresses. Structural engineers acknowledge that this is a rather crude approach, but maintain that it is adequate for low buildings. It is agreed by many that, in an area of high seismic hazard, dynamic analysis is preferable for high buildings and high–risk facilities. Dynamic analysis involves detailed quantitative modelling of a structure and its behavior (i.e. its deflections and internal stresses) when subjected to earthquake shaking. Dynamic analysis is more realistic than pseudostatic analysis, but requires extensive use of computers. The very same techniques can be used to calculate the response of near–surface earth materials, and the resulting site–specific ground motion can be computer analyzed in a structural model. It may be quite costly to determine the dynamic mechanical (engineering geophysical) properties of earth materials needed to perform the analysis; however, simplifying assumptions often can be made.

Seismic risk (i.e. the probability of property loss or human injury) is a function of naturally occurring seismic hazards and the earthquake's resistance of the works of man. Where there are no man–made structures, seismic risk is extremely small. Planners concerned with environmental health and safety are interested in predictions of seismic risk; however, such forecasts are very difficult to make because they involve a number of physical phenomena which are either poorly or inadequately understood.

Prediction of seismic risk means prediction of the following: the location, magnitude, and frequency of earthquakes; vibratory motion in rock; the response of unconsolidated earth materials to these rock motions; and the response of man–made structures to resultant ground surface motions. The disciplines of seismology, geology, and soils and structural engineering must all be used, and expert practitioners in each of these fields will admit to very significant uncertainties in predictions of the phenomena with which they deal.

This report describes, in very broad terms, the kinds and levels of ground shaking and liquefaction hazards in Sonoma County. Precise hazard levels cannot be predicted for any articular place; however, the information presented here will focus attention on the nature and gross geographic distribution of these hazards.

Two important quantities are essential to understanding and interpreting seismic effects: earthquake magnitude and intensity of ground shaking. Magnitude, derived from seismograph records, is measured on the Richter scale and is a unique value, within narrow limits, for each earthquake. The scale is logarithmic, and each whole unit represents an increase of about 30 times in the energy released. The largest known earthquake had a magnitude of 8.9 (Richter, 1958, p. 350).

Table 2. Modified Mercalli Intensity Scale of 1931[1] (1956 version)[2].

Masonry A, B, C, D. To avoid ambiguity of language, the quality of masonry, brick or otherwise, is specified by the following lettering:

Masonry A. Good workmanship, mortar, and design: reinforced, especially laterally, and bound together by using steel, concrete, etc.; designed to resist lateral forces.

Masonry B. Good workmanship and mortar; reinforced, but not designed in detail to resist lateral forces.

Masonry C. Ordinary workmanship and mortar; no extreme weaknesses like failing to tie in at corners, but neither reinforced nor designed against horizontal forces.

Masonry D. Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally.

I.	Not felt. Marginal and long-period effects of large earthquakes.
II.	Felt by persons at rest, on upper floors, or favorably placed.
III.	Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.
IV.	Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV wooden walls and frame creak.
V.	Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate.
VI.	Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knickknacks, books, etc., off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D cracked. Small bells ring (church, school). Trees, bushes shaken visibly, or heard to rustle.
VII.	Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices also unbraced parapets and architectural ornaments. Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.
VIII.	Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.
IX.	General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. General damage to foundations. Frame structures, if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated areas sand and mud ejected, earthquake fountains, sand craters.
X.	Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.
XI.	Rails bent greatly. Underground pipelines completely out of service.
XII.	Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

[1] Original 1931 version in Wood, H. O., and Neumann, F., 1931, Modified Mercalli intensity scale of 1931: *Seismological Society of America Bulletin*, v. 53, no. 5, p. 979-987.

[2] 1956 version prepared by Charles F. Richter, *in Elementary Seismology*, 1958, p. 137-138, W. H. Freeman & Co.

Table 3. History of damaging earthquakes in Sonoma County*

Date	*Location*	*MMI I***	*Damage*
03/08/1865	Santa Rosa	VII	Severe in Bennett Valley
01/03/1876	Fulton–Freestone	VI–VII	Walls cracked
02/29/1888	Petaluma	VII	Walls cracked
10/11/1891	Sonoma Valley	VII–VIII	Many chimneys fell; every house in Sonoma Valley was damaged to some extent
08/09/1893	Santa Rosa	VII	Many chimneys damaged, slight damage in Petaluma
10/12/1899	Santa Rosa	VII	Some chimneys down; some damage at Petaluma
04/18/1906	San Andreas fault	X+	Severe damage in Santa Rosa Valley (see text of report)
04/25/1968	Santa Rosa	VII	Chimneys and plaster damaged. Magnitude 4.6
10/01/1969	Santa Rosa	VII–VIII	Building damage $6 million; a number of old brick and frame buildings were damaged beyond repair. Two shocks, magnitude 5.6 and 5.7

* Data from Caffman and von Hake, 1973.
**Modified Mercalli intensity (see table 2).

Intensity of ground shaking resulting from an individual earthquake varies from area to area and is strongly dependent upon distance from the source. It is assessed by the observation of seismic effects on people, on the land, and on structures. Intensity values assigned are based on the Modified Mercalli Intensity Scale of 1931. Maps of the intensities produced by an earthquake commonly portray zones of equal intensity. More precise and quantitatively useful methods of measuring local ground response, based on strong motion seismograph (accelerograph) records, are being developed in earthquake science.

Seismicity

HISTORY OF DAMAGING EARTHQUAKES

Since 1855, more than 140 local earthquakes have been felt in the Santa Rosa Valley area (Cloud and others, 1970), and ten of these were damaging (table 3). In addition, the 1868 earthquake on the Hayward fault caused considerable damage in Petaluma and Santa Rosa. The wo most destructive earthquakes in Sonoma County history were those of 1906 and 1969, and some discussion of them may provide useful clues to possible future events.

1906 Earthquake

The San Francisco earthquake of April 18, 1906, with a probable Richter magnitude of 8.25, was one of the most severe earthquakes in California history. It was caused by rupture along the San Andreas fault for 190 miles or more, from San Juan Bautista, San Benito County, to Point Arena or perhaps Shelter Cove, Humboldt County. Horizontal displacement of the ground along the fault rupture averaged 15 feet; vertical displacement was generally less than two feet. As in all earthquakes, building damage varied considerably according to ground conditions, as well as distance from epicenter or fault rupture. In 1906, building damage was generally confined to the zone within 30 miles of the fault (Lawson and others, 1908, p. 199–210).

Santa Rosa.—According to Lawson and others (1908), "Santa Rosa suffered relatively more than any other place in California, except perhaps Sebastopol and Fort Bragg ... The shock of April 18 and the ensuing fire caused a loss of life of 61 identified dead, with at least a dozen 'missing', and practically destroyed the business portion of Santa Rosa. The equivalent of some 7 to 8 blocks was destroyed by the earthquake, and from 4 to 5 blocks by the fire ... The residence portion of the town suffered to quite an extent. Chimneys were generally thrown down or so badly cracked as to necessitate their rebuilding. From 20 to 25 residences were thrown to the ground by the collapse of their underpinning, and badly wrecked ... The physiographic results of the shock seem to be confined to some minor cracks in the vicinity of the cemetery with the possible addition of some small cracks near the the creek bed adjacent to the tannery ... Mr. J.C. Parsons, City Engineer, reports that he has found no changes in alignment since the shock. He thinks there are no changes in level, but has not yet made any accurate measurements of level. No disturbances of streets or sidewalks were found, such as are common in San Francisco."

The most marked physiographic effects in the vicinity of Santa Rosa were found near the cemetery slightly more than 1 mile northeast of the central square. A 200–foot–long crack along the side of a swampy depression just north of the cemetery hill and a 100–foot–long crack along the north end of the hill were reported. At the County Hospital, a little less than 1 mile north of the cemetery, low ground at the foot of a small hill sank 2 feet and springs were formed.

Lawson and others (1908) attribute the great damage to "physiographic conditions" and the weakness of the buildings. Much of the town was constructed over filled–in stream channels and ground water was quite shallow in the early spring at the time of the shock. The weakness of masonry construction was apparently due to the use of sand with high loam content in preparing the mortar.

The fact that no changes in alignment or level or disturbance of streets and sidewalks were observed suggests that liquefaction did not occur in Santa Rosa. Perhaps ground shaking was amplified by the presence of loose fill in old stream channels and by the saturation of alluvium at shallow depths. Probably poor quality mortar was the principal factor in the extensive destruction of brick buildings.

Vicinity of Sebastopol.—In Sebastopol, several buildings were demolished. The Knowles Hotel, a two–story frame building veneered with brick, collapsed. A new frame house was moved 3 to 8 inches on its concrete foundation, causing the walls to crack and wrench. The Sebastopol Cemetery was more severely damaged than the one at Santa Rosa; nearly 90 percent of the larger monuments were thrown down. Many frame buildings around Sebastopol were thrown off their foundations.

Vicinity of Petaluma.—In Petaluma, most chimneys fell. In east Petaluma, on the lowland, all but four fell. Masonry buildings fared poorly and a number of walls collapsed. "There are no authenticated reports of (ground) cracks in Petaluma nor in the low tidal lands immediately adjoining. Vague reports to this effect were not verified" (Lawson and others, 1908). At Lakeville, about 6 miles southeast of Petaluma, chimneys were knocked down. Northeast of Petaluma, chimneys fell down in the lowland areas and on Sonoma Mountain; no landslides or cracks were reported.

Sonoma Valley.—Most chimneys fell, but masonry buildings were generally either undamaged or only slightly damaged. Even adobe buildings escaped serious damage.

Healdsburg.—"This place comes next to Santa Rosa in the extent of damage done to towns in Sonoma County. The shock was definitely less severe, however ... Not a building escaped damage to some extent, whether made of wood, brick or stone. There were five brick buildings destroyed. Along the creek and river bottoms the earth was fissured and water was forced up which, in some instances, flooded the orchards" (Lawson and others, 1908, p. 183–184).

Western Sonoma County.—Brick buildings at Valley Ford, Bloomfield, and Bodega were wrecked, and frame buildings were shifted off their foundations. A large number of cracks formed in the flat valley bottom adjacent to the town. At Bodega, good frame buildings with strong foundations were not damaged.

1969 Santa Rosa Earthquakes

On October 1, 1969, two moderate earthquakes, with magnitudes 5.6 and 5.7, occurred on the southern end of the Healdsburg fault on the north side of Santa Rosa. These shocks are of substantial interest because of unexpected damage to earthquake–resistant buildings and because of the concentration of dwelling damage into a relatively small area. "The earthquakes were not strong enough to cause building collapse, although one major brick wall partially fell, other brick walls were cracked or partially failed, hundreds of brick chimneys toppled, and a number of older wood–frame dwellings fell off their foundations or were otherwise seriously damaged" (Steinbrugge and others, 1970, p. 2). No deaths occurred, but about 15 persons were treated in hospitals; most injuries were lacerations from broken glass. Losses to commercial and public buildings were estimated at $2 million and losses to dwellings at $4 million (Steinbrugge and others, 1970, p. 3).

Principal damage to nondwelling construction was in the older commercial areas. Most damaged structures were brick–bearing wall buildings with sand–lime mortar; none of the damaged brickwork was reinforced. A few older buildings with reinforced concrete walls and wood floors also were damaged. There was significant structural damage to three modern earthquake–resistant buildings: the Sonoma County Social Service Building, the Sonoma County Fairground grandstand, and the Crocker–Citizens Bank Building (Steinbrugge and others, 1970, p. 4–5).

Earthquake damage to dwellings in Santa Rosa — generally one–story, wood–frame buildings — was greater than that experienced in recent California earthquakes of similar Richter magnitudes. Apparently age was an important factor, as the majority of houses damaged were built before 1940; post–1940 houses were not seriously damaged. A number of heavily damaged houses were in such poor repair before the earthquake that abatement proceedings were being considered. The locations of damaged houses suggest a pocket of high earthquake intensity, but because the large majority of older buildings were also concentrated in this area, it is difficult to draw conclusions about geographic variation of ground shaking (Steinbrugge and others, 1970, p. 5–7).

Widespread breaks occurred in the eastern part of town in water system pipes, sidewalks, curbs, and street pavements. None of these breaks appears to have resulted from surface fault displacement; apparently permanent deformation of the underlying alluvium in the form of lurching, or collapse of unconsolidated fill, was responsible. However, the fact that these effects were largely confined to a north–northwest–trending zone 2 miles long and more or less in line with the fault plane determined for the earthquake suggests that ground motion was especially strong directly over the fault (Steinbrugge and others, 1970, figure 57; Cloud and others, 1970, p. 45).

Intensity Recurrence

Figure 2 shows that the frequency of occurrence of strong ground shaking (intensities VI, VII, and VIII) has been nearly as great in Santa Rosa Valley as in the entire San Francisco Bay region. Extending the data period up to the present, thus including the 1969 Santa Rosa earthquakes of intensity VII–VIII, would bring the two curves even closer together.

If the last 160 years are fairly representative of long–term seismicity of the Bay region, potentially damaging ground shaking (intensity VII or greater) should be expected about once every 30 years in the Santa Rosa Valley.

EARTHQUAKE MAGNITUDE VERSUS RECURRENCE

The greater San Francisco Bay region, extending from Monterey Bay on the south to Ukiah on the north and to Vacaville on the east, is one of the most seismically active areas of California. *Seismicity* was much higher in this region during the nineteenth century than it has been in the twentieth; since the strong 1906 earthquake, a few moderate shocks (magnitude less than 6.0) and no major shocks have occurred. However, between 1836 and 1906 there were 5 major (magnitude probably greater than 7.0) and a number of moderate shocks. The following analysis of magnitude versus frequency of occurrence demonstrates and interprets this temporal change in seismicity.

The region covered by the Geologic Map of California, Santa Rosa Sheet (Koenig, 1963), was chosen for analysis (figure 3) because it affords a fair sample of seismic activity. The reliability of magnitude–frequency curves as indicators of future seismicity is proportional to the time–area sample of past seismicity used to prepare them. There is good reason to believe that the 28–year record (1944–1971) for the Santa Rosa Sheet area and the 30–year record (1932–1961) for the central Coast Ranges are poor indexes of future seismicity. This is probably due to the fact that the 1906 earthquake released nearly all the accumulated strain in the central Coast Ranges area; thus seismicity has been abnormally low since that event. On the other hand, it could be argued that seismicity was abnormally high in the 100–year period immediately preceding the 1906 event due to an unusually high level of strain. Perhaps the long–range average seismicity for the region falls between that of the pre– and post–1906 periods. The conservative approach is that the pre–1906 period is more representative of long–term seismicity, taking into account the facts that pre–1906 earthquakes were not as well reported as those since 1906 and that only crude estimates of magnitude are available for the period before 1932.

Table 4 and Figure 3 show that, for the period 1944 to 1971, the unit–area (1000 km^2 or 12,000 km^2) seismicity of the Santa Rosa Sheet is similar to that of the larger central Coast Ranges area for magnitudes 6 and greater. This suggests that the region covered by the Santa Rosa Sheet and the rest of the central Coast Ranges are subject to comparable tectonic forces. Therefore, the long–term unit–area seismicity of the two regions should be similar, and the recurrence intervals for the central Coast Ranges for 1810–1931 are believed to be a reasonably good indicator of future seismicity in the Sonoma County region. Geodetic and geologic data bearing on the long–term displacement rate along the San Andreas fault suggest a recurrence interval of from 50 to 200 years for earthquakes of magnitude 8 or greater along the total length of the fault (Wallace, 1970, p. 2886). This is in satisfactory agreement with the seismicity data.

If seismicity is assumed to be evenly distributed throughout the region covered by the Santa Rosa Sheet, the data discussed here indicate that potentially damaging ground shaking (Modified Mercalli intensity VII or greater) should occur somewhere in the County every 20 to 30 years. This is in fair agreement with the estimated 30–year recurrence of intensity VII or greater earthquakes in the Santa Rosa Valley area based strictly on intensity data.

EPICENTER DISTRIBUTION AND ACTIVE FAULTS

Plate 4 shows earthquake epicenters located by the Seismograph Station at the University of California, Berkeley, for the period 1910–1971. Since 1963, epicenters located by the Seismograph Station in this area are accurate to within 5 km for magnitude 3.5 or greater shocks. Before 1963, accuracy of epicenter locations ranged from about ±20 km in 1910 to ±20 km in 1962 (McEvilly, 1974). For this reason one cannot see distinct clustering of U.C.–located epicenters along the active Rodgers Creek fault system nor along any other faults.

Immediately following the Santa Rosa earthquakes in 1969, the National Center for Earthquake Research (NCER) of the United States Geological Survey (USGS) extended its dense Bay area seismograph network into the Santa Rosa Valley area. Plate 4 shows USGS–located epicenters and stations on the Santa Rosa Sheet for the

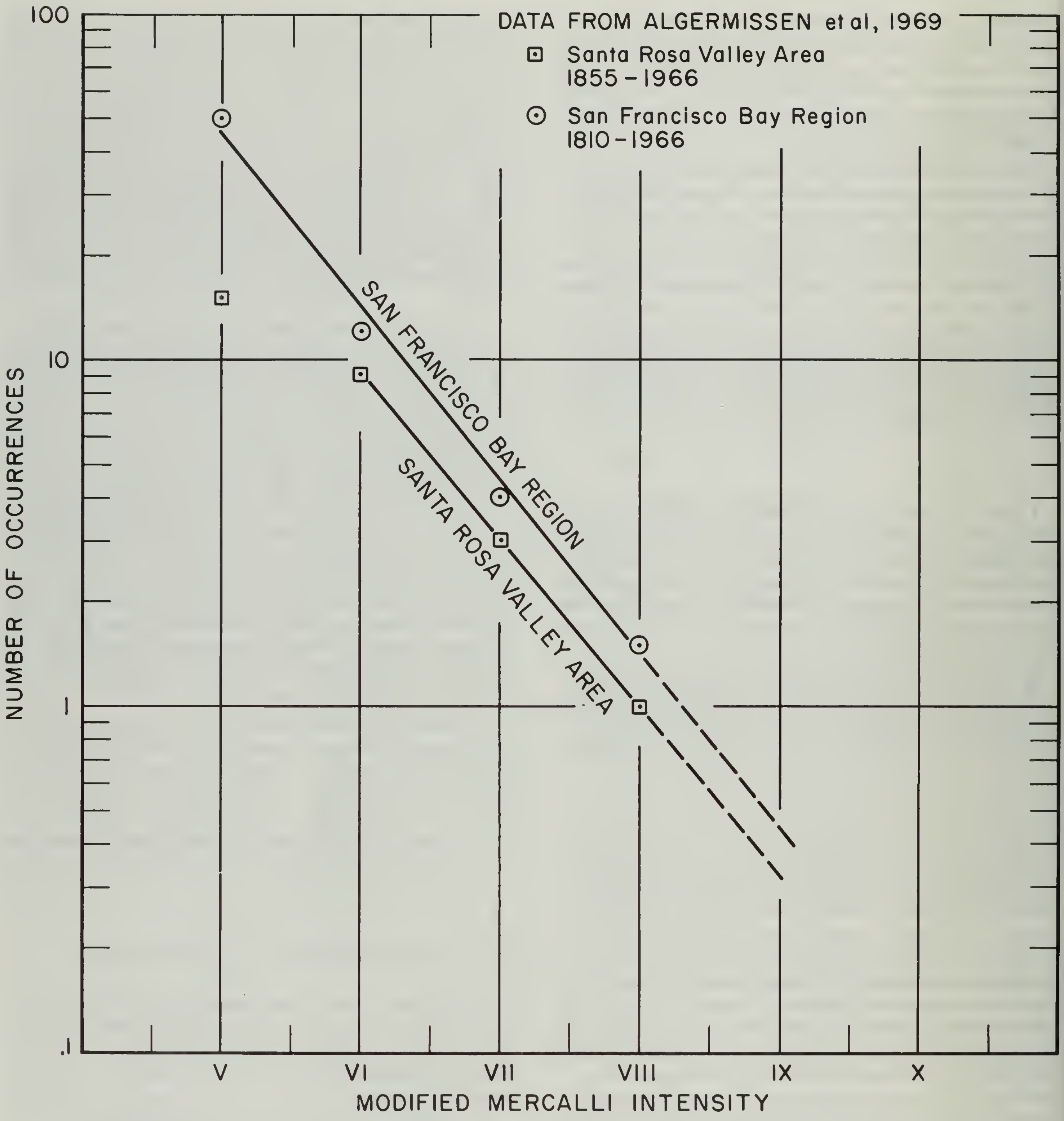


Figure 2. Intensity recurrence: Santa Rosa Valley region

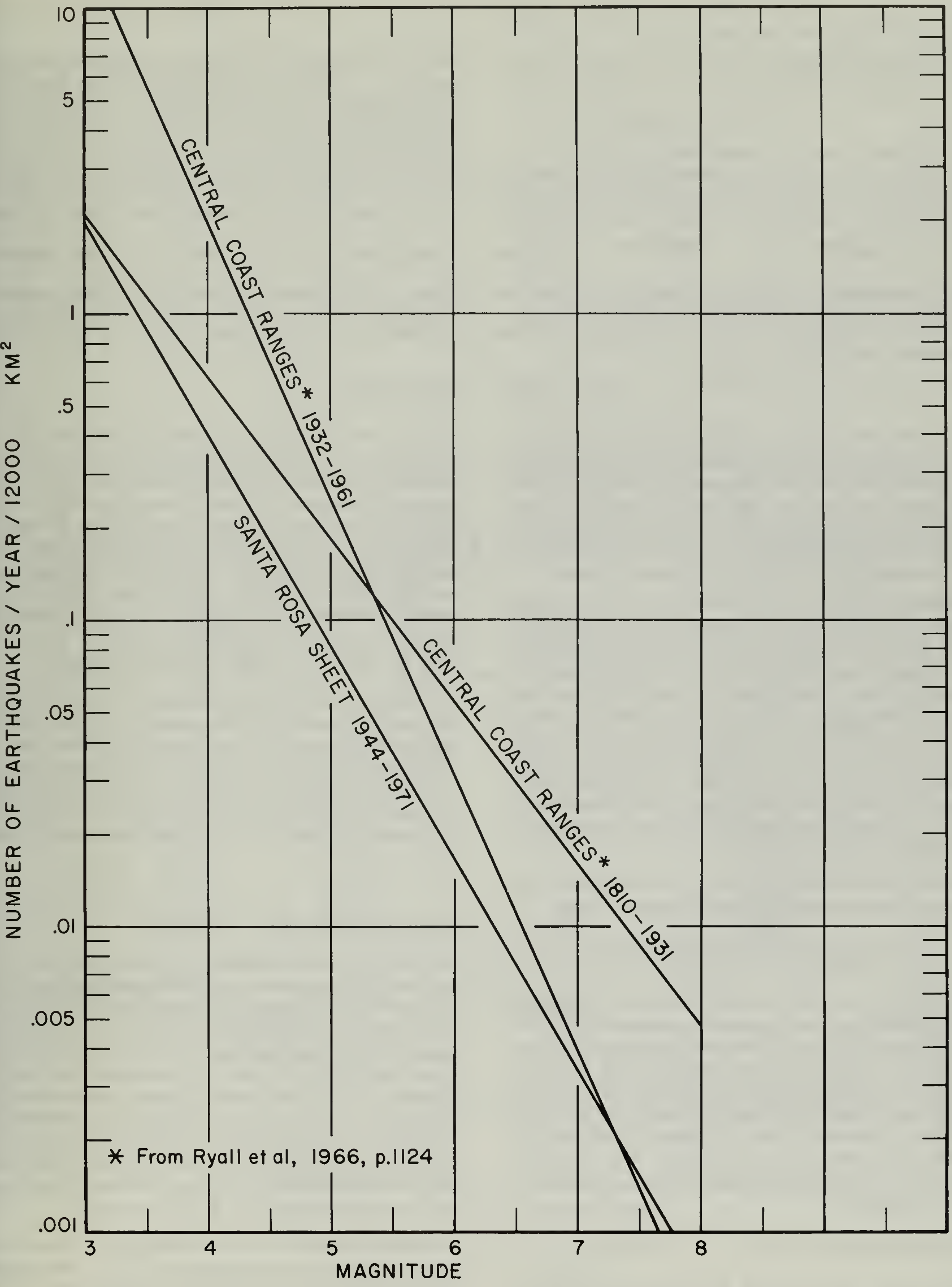


Figure 3. Magnitude vs. frequency of occurrence for the Sonoma County region

Table 4. Earthquake recurrence intervals for the Sonoma County region (see figure 3).

Region	Earthquake Data Set Area (km^2)	Period (years)	Recurrence Parameters*		Average Recurrence Intervals (yrs.)				
					1,000 km^2		12,000 km^2**		
			a	b	6	7	6	7	8
Santa Rosa Sheet	12,000	1944–1971	1.42	0.72	720	3600	60	300	1500
Central Coast Ranges	33,000	1932–1961	2.83	0.90	370	2960	32	250	2000
Central Coast Ranges	37,000	1810–1931	0.84	0.53	216	735	18	62	210

* Parameters of the equation log $N = a-b M$; "a" is normalized on an annual and per 1000 km^2 basis. For the central Coast Ranges, "a" and "b" are from Ryall and others, 1966, p. 1124.

**Approximate land area on Santa Rosa sheet.

period 1969–1973, and a correlation between epicenters and the mapped traces of the Rodgers Creek–Healdsburg fault system. This correlation appears because of the relatively high accuracy and precision of the USGS data. Epicenter locations are accurate to within 2 km. Most of the epicenters at the southern end of the Healdsburg fault are aftershocks of the 1969 Santa Rosa earthquakes.

Both the USGS and UC Berkeley data indicate a lack of seismicity along the San Andreas fault; this is characteristic of the fault northward from the Santa Cruz Mountains to Point Arena. There is very little seismicity west of the Rodgers Creek–Healdsburg fault zone but a great deal of it to the east. This could be a result of the 1906 earthquake which probably released most of the stored crustal strain energy in the western part of the area. Crustal strain apparently is still at a low level there, but geodetic measurements at Fort Ross and Point Reyes (Greensfelder, 1972, p. 9) indicate that strain is accumulating along the San Andreas fault.

Seismicity east of the Rodgers Creek–Healdsburg fault system has not been correlated with mapped faults.

Seismically Induced Ground Motion

As discussed in this report, potentially damaging ground shaking may be expected to recur every 20 to 30 years in Sonoma County. Data are insufficient to define the character of future ground shaking in the alluviated areas of the County, the areas most susceptible to this seismic hazard. However, the characteristics of anticipated shaking in rock are known and provide input data for calculations to predict the general nature of ground shaking at the surface in alluvial valleys where most urbanization is expected.

MAXIMUM SHAKING IN ROCK

Maximum shaking in rock is commonly specified in terms of "maximum credible" and "maximum probable" accelerations. Maximum credible acceleration at any given place is the maximum acceleration that could ever reasonably be expected to occur there, given the known geologic framework. It is based entirely on the location, length, and relative recency of displacement on faults in the region surrounding the site under consideration. Maximum probable acceleration at a site is the strongest acceleration expectable within a given span of years. It is derived from statistical analysis of the recorded seismicity of the surrounding region and is, therefore, always less than or equal to maximum credible acceleration.

Shaking is not completely described by maximum acceleration as defined in the paragraph above; the duration and spectral character of each particular event (i.e. the distribution of amplitude relative to vibrational period) must also be known. As an additional factor, the numerical value of any rock acceleration may be modified by topography, but this factor is not well understood (Nason, 1971).

Maximum Credible Rock Acceleration

Two major faults in Sonoma County were selected for analysis. The maximum credible Richter magnitude is 8.5 for earthquakes on the San Andreas and 7.5 for those on the Healdsburg–Rodgers creek fault. These estimates are based on the observed rough correlation between earthquake magnitude and length of associated surface faulting (Bonilla, 1970, p. 66). Curves relating peak acceleration, earthquake magnitude, and distance from causative fault (Schnabel and Seed, 1973, p. 506) indicate that any place in the County should have a peak rock acceleration ranging from a minimum of 0.45g to more than 0.75g, depending on its position relative to the two faults.

Maximum duration of strong shaking for these earthquakes should be approximately 30 to 40 seconds. Predominant period of vibration should be about 0.3 seconds (frequency about 3 cycles per second).

Maximum Probable Rock Acceleration

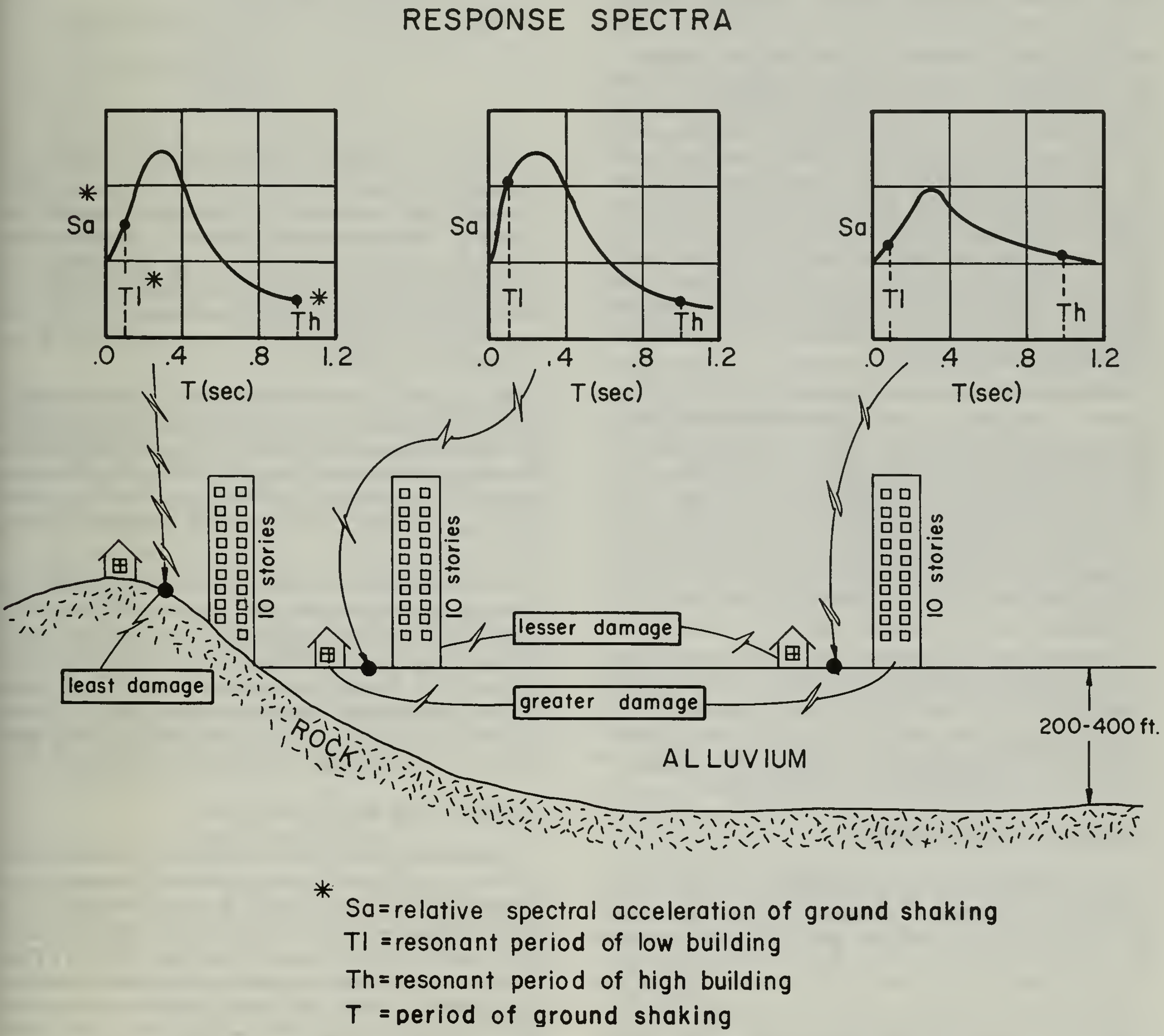
It is estimated that maximum probable rock acceleration, based on the magnitude and intensity recurrence data cited above, would fall in the range 0.3g and 0.7g for an average 100–year period, depending on location relative to the two active faults. Predominant period and duration would be roughly as indicated under "Maximum Credible Rock Acceleration" above, except that duration would be shorter, in the range of 20 to 30 seconds.

GENERAL CHARACTERISTICS OF GROUND SHAKING

Various studies have related types of surficial geologic material to relative intensity and observed damage (Barosch, 1969; Richter, 1959, p. 129; Gibbs and Eaton, 1971). These studies show that bedrock and water–saturated alluvial sites demonstrate the greatest contrast intensity — up to four units on the Modified Mercalli Scale in a given great event and probably three units in a more usual earthquake.

The relative susceptibility to strong ground shaking of differing materials is reflected on Plates 1A and 1B, where areas of Quaternary alluvial materials taken from the "Geologic map exclusive of landslides" (plates 3A and 3B) have been assigned a higher relative ground shaking hazard.

Careful quantitative definition of the characteristics of shaking in alluviated areas where urbanization is expected



* Sa=relative spectral acceleration of ground shaking
Tl =resonant period of low building
Th=resonant period of high building
T =period of ground shaking

Figure 4. Schematic representation of relationship between geology, response spectra, building height, and potential damage in a strong local earthquake

to largely concentrate is not possible without gathering and analyzing a tremendous mass of close-spaced detailed data. Nevertheless, it is possible to make a few generalizations which will provide planners and engineers with a qualitative concept of the problem.

Generally, it is not maximum ground acceleration but rather the spectral character and duration of ground acceleration that govern the behavior of man-made structures in an earthquake. Spectral character is defined by a "response spectrum" which is calculated from a time history of acceleration during each event — usually an accelerogram recorded by a strong motion accelerograph (Housner, 1970, p. 85). Response spectra are commonly used by structural engineers in designing major buildings and critical facilities, such as hospitals, major dams, and nuclear power plants, to be earthquake resistant. The shape of a response spectrum at a particular place is strongly influenced by the mechanical properties of the underlying earth materials; the magnitude and distance of the earthquake from that place also influence the spectrum. Variations in type, geometry, and thickness of soil and alluvial deposits are particularly important, as has been demonstrated in numerous publications on the subject. Seed and Schnabel (1972) have shown a strong correlation between building damage, building height, and thickness of alluvium in Caracas Valley for the 1967 Caracas, Venezuela, earthquake. Generalized, their results show a direct relationship between building height, greater building damage, and thickness of alluvium underlying damaged buildings. This resonance effect is illustrated schematically in Figure 4.

Given an appropriate acceleration time history (observed or synthetic) in rock, and dynamic mechanical properties of the overlying soil and alluvium, response spectra at the ground surface can be calculated by various numerical techniques. In a proposed continuation of this study, the Division of Mines and Geology could develop formats for the kinds and amounts of geologic and geophysical data needed to make reasonably reliable calculations of response spectra in selected alluvial areas of the County.

Plates 1A and 1B show the distribution and approximate maximum thickness of alluvium. Although these data cannot be used to predict spectral ground acceleration, they suggest the areas in which high-rise structures would be more strongly shaken (i.e. for the thickness of alluvium ranging from about 50 to 400 feet).

Estimation of Alluvial Thickness

The alluviated areas have been divided into five zones based on the thickness of alluvium believed to be present. For several reasons it was not possible to draw isopachs of the alluvial thickness. Time did not permit assembling and analyzing all the drillers' logs of water wells in the County. In most instances, the alluvial material lies either on the Glen Ellen or Huichica Formations. These nonmarine beds are so similar in lithology to the alluvium that it is very difficult or impossible to differentiate them from the drillers' descriptions.

Throughout most of the County, the alluvium occurs in long, narrow stream and river valleys that have a buried ancient topography. The distribution of water wells that may have penetrated to this older surface is so irregular that a meaningful contour map could not be drawn.

Therefore, drawing from data and conclusions presented in water supply papers (Cardwell, 1958; Kunkel and Upson, 1960) and considering the lower sea levels during the Pleistocene epoch, the areas were divided into zones which reflect the maximum depths to bedrock. Since the thickness varies from zero at the edges to a particular maximum, the zones are presented as follows:

Zone	Thickness
1	0 – 50 feet
2	0 – 100 feet
3	0 – 150 feet
4	0 – 200 feet
5	0 – 300 feet

In the lower reaches of the major drainages, such as the Russian River near Jenner and the marshy areas south of Petaluma and Sonoma, unconsolidated materials are probably 300 feet or so in maximum thickness. These materials represent the deposits of the *aggrading rivers* and streams as the sea level rose during the present *interglacial period.* Thicknesses diminish upstream from the mouths of the drainages and are probably less than 50 feet in most of the upland areas.

The area from near Santa Rosa to the Cotati Valley is difficult to evaluate. There is disagreement between geologists as to the nature of much of the surface sediments in the central and northern parts of the area. They have been mapped both as Quaternary alluvium (Fox and others, 1973) and as Glen Ellen Formation (Blake and others, 1971).

If the Glen Ellen Formation crops out as shown, the alluvium probably is quite thin, from 0 to 50 feet in the south to ± 70 feet around Santa Rosa and possibly 100 feet to the north. However, if the surface material is older alluvium, as recently interpreted by Fox and others (1973), the thickness may be somewhat greater — probably 0 to 50 feet in the extreme south, but reaching about 100 feet at Santa Rosa and 150 feet to the north.

LIQUEFACTION AND ITS EFFECTS

Liquefaction is the transformation of a granular material from a solid into a liquefied state as a consequence of increased *pore-water pressure.* By itself, it may pose no hazard; however, when it leads to some form of ground movement or failure it may be a serious problem (Youd, 1973, p. 6). It is a common occurrence in water-saturated, sandy deposits subjected to strong earthquake shaking and is the proximate cause of low-angle-flow and lateral-spreading landslides, lurch cracking, and "quick-condition" failures (Youd, 1973, p. 8–9). Youd and others (1973) showed that unconsolidated sediments that are most susceptible to liquefaction contain the relatively greatest abundance of saturated, low–density, clay–free granular materials. Examples would be the loose sand and soil deposits along present and former stream channels within the younger bay sediments, or "bay mud", adjacent to San Pablo Bay. Other alluvium at higher elevations would be saturated only periodically by high ground water levels. Relatively older materials would be more consolidated, with weathered, clay–rich soil profiles. Hence, their liquefaction potential would be relatively lower. The following relative potential ratings were proposed for the southern San Francisco Bay region (Youd and others, 1973, p. 13):

GEOLOGIC UNITS	LIQUEFACTION POTENTIAL OF CLAY–FREE GRANULAR LAYERS
Pleistacene alluvial fans	Generally law
Holocene alluvial deposits	Moderately law; water table narmally below 10 ft (3m)
Halacene alluvial depasits	Maderately low; water table narmally abave 10 ft (3m)
San Francisca Bay sediments	Generally maderate; lacally high where clean granular layers lie within yaung bay sediments

Using similar principles and based upon the inferred relative abundance of liquefiable materials, Plates 1A and 1B differentiate relative liquefaction potential into three categories, from lowest to highest: bedrock, valley alluvium, and younger bay mud. Distribution of these was derived from the "Geologic map exclusive of landslides".

Liquefaction–induced ground failure may be an important problem in Sonoma County, where the ground water table in alluvial areas is generally not more than 10 to 20 feet deep. During the 1906 earthquake, liquefaction apparently occurred near the Santa Rosa Cemetery and in the Russian River flood plain, but not in Santa Rosa itself (see p. 8). In the 1969 earthquakes, liquefaction may have contributed to the ground failures that damaged pipes, streets, and curbs (see p.9).

FAULT RUPTURE

The strongest tectonic forces acting in California are the opposing crustal forces of the northwest–moving Pacific plate and the southeast–moving North American plate. These crustal plates concentrate most of their stress (a compressional force) along the coast of California. The resulting strain is largely relieved by displacement along a series of northwest–southwest–trending strike–slip faults and eastwest–trending reverse (thrust) faults (figure 5). The sense of movement for the strike–slip faults is usually right–lateral, thus helping the Pacific plate to slip by the North American plate. Friction along the faults creates a resistance which must be overcome before the faults can move.

Resistance to movement varies not only from fault to fault, but also along the length of each fault. Some portions of a fault remain locked for long periods of time; other portions are creeping constantly. Slippage at a locked portion of a fault usually involves a sudden displacement of several feet accompanied by a relatively large earthquake. Movement along creeping portions of a fault is usually measurable only with time and is accompanied by relatively small earthquakes or none at all. The lapse of time between movements (recurrence interval) is long (tens to thousands of years) for a locked fault portion, and short (several months) for a creeping portion.

Displacement rarely is limited to a single fault plane but more often affects an array of related fault planes. The surface expression of these fault planes is a closely spaced group of ground breaks known as a fault zone. The width of a fault zone can be anywhere from a few feet to several miles, and identifiable breaks within the zone could conceivably number in the hundreds. The common arrangement of the breaks or trace within a fault zone is parallel or near–parallel. Some breaks are connected with a braided pattern; others appear to be unconnected *en echelon*. Movement does not always recur along the same break, nor is it always limited to a single break. The most widely held opinion is, however, that recurrence of movement is most probable along that break on which the last apparent movement took place.

Although the number of faults and fault zones in California is large, only a small number of them are thought to be active (and thus considered to be geologic hazards). If recurrence of movement along a fault or fault zone is thought to be probable, the fault has been labeled potentially active. Potential future activity of a fault is evaluated by the recency of past activity. All faults that appear to have been active during Quaternary time (beginning 2 to 3 million years ago) are considered to be potentially active unless there is positive evidence that they have been inactive for the last 10,000 to 12,000 years (Holocene Epoch).

The more recent the evidence of past movement, the greater the probability of future movement. If a fault has displayed movement recent enough to have been recorded by man, it is historic. This could be a measurable slippage accompanying a large earthquake, or fault creep manifested in the wrenching or cracking of a man–made structure straddling the fault. Usually a coincidence of earthquake epicenters also is located along such faults. Probability of future movement along historically active faults is very high and recurrence intervals can sometimes be computed for them.

Holocene faults have not displayed historic movement but do exhibit characteristics indicative of activity during

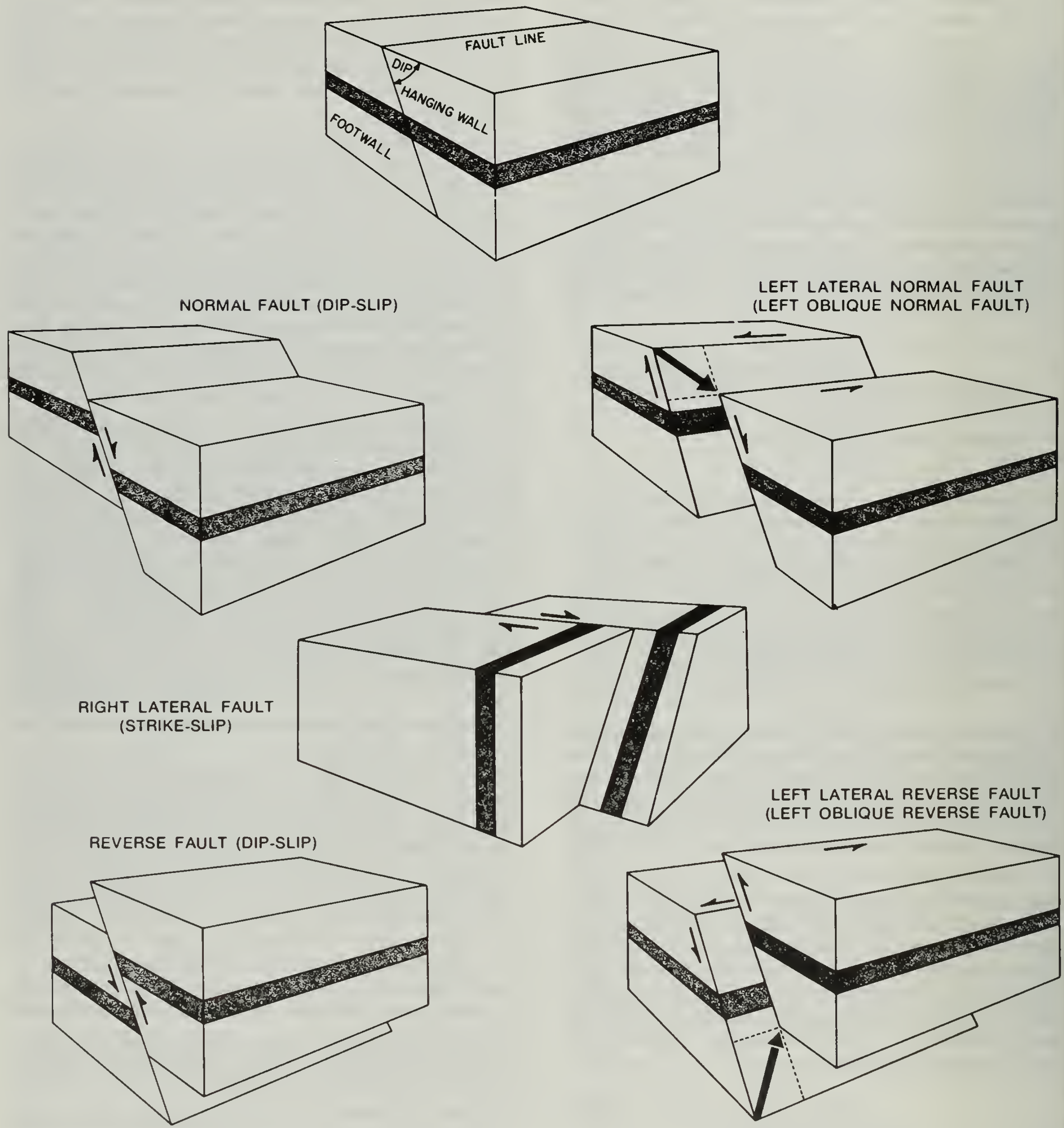


Figure 5. Types of fault movement

the Holocene Epoch. For instance, if a fault trace displaced geologic deposits of Holocene age or is defined by a path of youthful, fault–related topographic features (e.g. scarps, sag ponds, shutter ridges, offset streams, linear ridges, and valleys as shown in figure 6), it is considered to be a Holocene fault and future activity is probable. Quite often earthquake epicenters are also coincident with such a fault.

Many faults showing evidence of having displaced rocks of Pleistocene age (as old as 2 to 3 million years), or of truncating other Quaternary faults, are considered potentially active if it cannot be shown that they have been inactive during Holocene time. Fault–related topographic features of Pleistocene age are less distinctive than Holocene features. Sometimes these faults are coincident with earthquake epicenters, but for seismological reasons this coincidence alone is not considered conclusive evidence of potential activity.

In compliance with the Alquist–Priolo Special Studies Zones Act, the State Geologist is in the process of delineating potentially active fault traces in California with appropriately wide Special Studies Zones. These zones are intended to control development for reasons of public safety. The criteria for the definition of potentially active faults used in this report are intended to match as nearly as possible the criteria used to identify faults for inclusion within the Special Studies Zones.

Seven potentially active faults or fault zones have been identified within the boundaries of Sonoma County: Burdell Mountain, Chianti, Healdsburg, Maacama, Rodgers Creek, San Andreas, and Tolay (see plates 3A and 3B). Most of the faults are thought to be steeply dipping, right–lateral, strike–slip faults. All have been identified on aerial photographs. In Sonoma County, The Chianti, Healdsburg, Maacama, Rodgers Creek, San Andreas, and Tolay faults are included within Special Studies Zones. Faults in Sonoma County are scheduled to be re–evaluated for Special Studies Zones in 1980. In addition, several possibly active faults are shown on Plates 3A and 3B. These faults exhibit features suggestive (but not conclusive) of potential activity. Further studies would be necessary to determine their degree of activity.

Potentially Active Faults

BURDELL MOUNTAIN FAULT

This fault is considered to be a complex reverse fault (Rice, 1973, p. 34–37) with topographic evidence of geologically young surface displacements.

CHIANTI FAULT

Noteworthy evidence of Quaternary movement on the Chianti fault are the right–lateral deflection of Gill Creek and the ponded alluvium immediately to the southeast (plate 3A). The right–lateral deflection of Big Sulphur Creek near its intersection with the fault probably also was controlled by faulting (Gealey, 1951, p. 32, 35).

North of Big Sulphur Creek the fault trace is apparently obscured by landslides. Preston Lake, on the projection of the fault near the County boundary, may be of fault rupture origin (Gealey, 1951, p. 35). Structural extension of the Chianti fault zone in the Kelseyville 15–minute quadrangle was mapped by McNitt (1968), and supplemental information was added by Blake and Wright (Blake and others, 1971). These authors did not ascribe activity to the fault, however. Inference of potential activity is based on the work of Gealey (1951) and aerial photo interpretation by Huffman. The potentially active fault shown on Plate 3 is a composite of the cited sources supplemented by aerial photographic interpretation during this study. The Chianti fault may be continuous with the possibly active Alexander Valley fault described below.

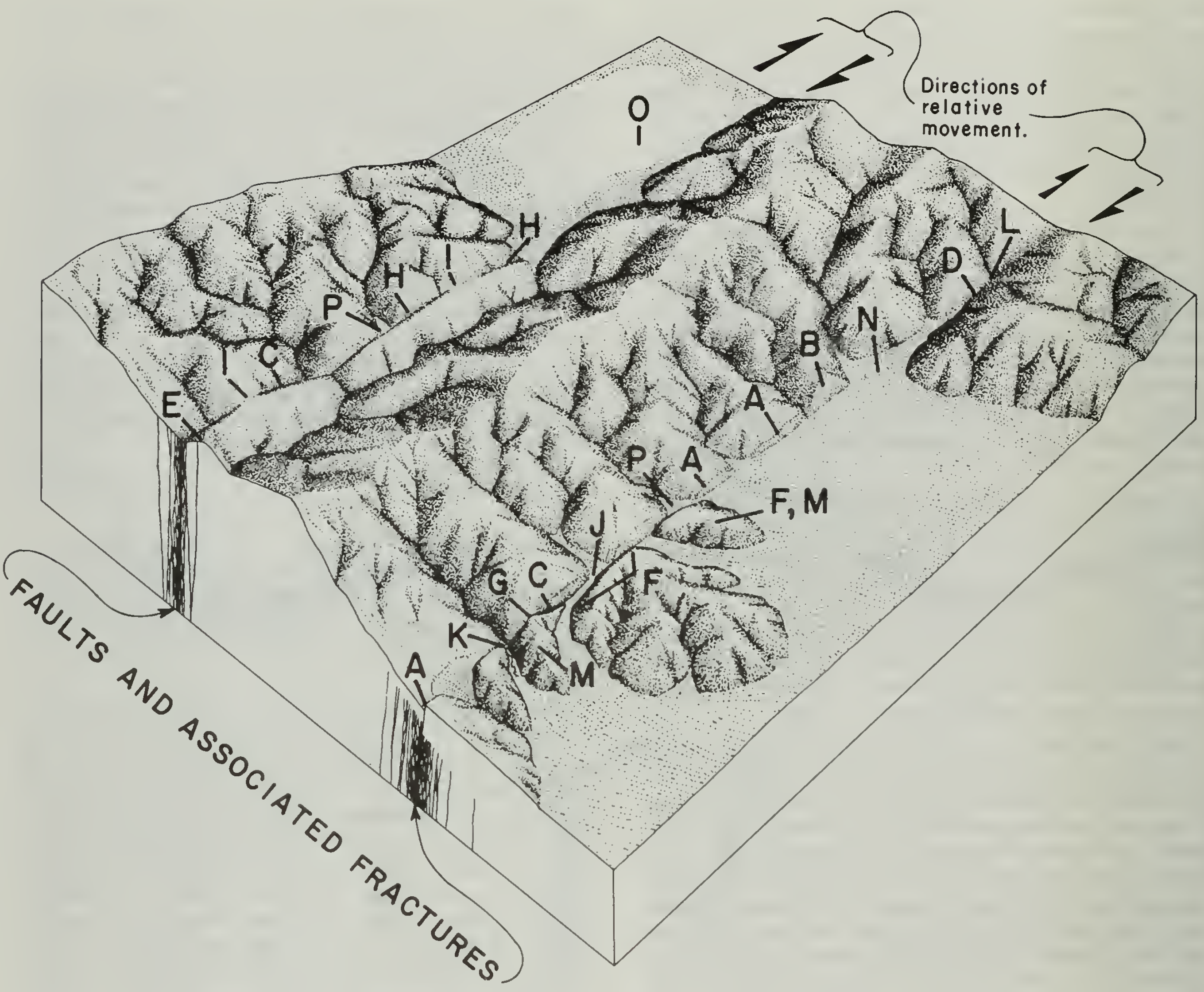
HEALDSBURG FAULT

Epicenters of the October 1, 1969, Santa Rosa earthquakes (magnitude 5.6, 5.7) and aftershocks are located near identified surface fault traces of the Healdsburg fault (plate 4). The quakes are inferred to have originated on this fault. No surface fault rupture occurred during these events, however.

The fault zone is complex, with numerous, often disconnected, parallel and divergent breaks. Its traces can be projected through the City of Santa Rosa, and a link with the Rodgers Creek fault to the south is possible. However, the nature of the linkage, if any, between these faults is uncertain. The fault zone merges with the Alexander fault zone of Gealey (1951, p. 36), who traced the combined faults north of the latitude of Cloverdale. This northward extension was not identified during the present study. The geology at the south end of the Healdsburg fault zone was mapped in detail by C.W. Jennings (1970) and this information was incorporated in the regional map by Fox and others (1973).

The queried fault segments on Plate 3A were shown on USGS–HUD Basic Data Contribution 12. However, limited aerial photo and field checking during this study and site investigations by consulting geologists have failed to confirm their presence.

Ponded alluvium, indicative of Quaternary surface rupture, was mapped by Gealey (1951, plate 1, p. 32, 36) north of Healdsburg and along branches of Windsor Creek northeast of Windsor (plate 3A). A fault contact between deformed Quaternary terrace alluvium and serpentinite is well exposed in recently constructed road cuts on Dutcher Creek Road 0.9 miles south of its intersection with Highway 101, and is continuous with the northern segment of Gealey's Alexander fault. Recently active fault traces were mapped by R.D. Brown Jr. (Blake and others, 1971; Fox and others, 1973). Potentially active traces shown on Plate 3A are derived largely from this source, supplemented by aerial photographic interpretation and minor field examination.


Directions of relative movement.
O
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A
FAULTS AND ASSOCIATED FRACTURES

A. Scarp
B. Faceted ridge
C. Linear gully, trench
D. Linear valley
E. Linear ridge
F. Shutter ridge
G. Notch
H. Hillside valley
I. Bench
J. Offset channel
K. Spring
L. Deflected stream or channel
M. Offset ridge
N. Depression; sag pond when wet
O. Depression (playa lake)
P. Ponded alluvium

Figure 6. Block diagram showing landforms produced along recently actives faults (modified from Clark, 1971)

MAACAMA FAULT

The westernmost break of the fault is well exposed in a road cut on Highway 128, where Quaternary terrace alluvium is faulted against tuff on the Glen Ellen Formation. Dorothy Radbruch–Hall of the U.S. Geological Survey has observed evidence of historic creep along a break of the fault approximately 1 1/4 miles southeast of Big Sulphur Creek (oral communication, 1974). Here, two fence lines are offset right laterally about 6 inches along the fault trace.

Strong geomorphic evidence of Quaternary surface movement also includes: ponded alluvium between Sausal and Gird Creeks and at the head of Crocker Creek (plate 3A); well–expressed, systematic, right–lateral diversion of drainages between Franz and Sausal Creeks; and tilting of the large Quaternary terrace south of the intersection of Maacama Creek and the fault (Gealey, 1951, p. 39).

The fault zone was mapped by Gealey (1951) in the Healdsburg 15–minute quadrangle and by McNitt (1968) in the Kelseyville 15–minute quadrangle. These data were compiled by Blake and others (1971). McNitt and Blake did not ascribe activity to the fault, however. The potentially active traces shown on Plate 3A are largely a product of aerial photographic interpretation by Huffman, guided by information cited above.

RODGERS CREEK FAULT

The southern extension of the Rodgers Creek fault zone is concealed by San Pablo Bay and the northern extension possibly extends under Santa Rosa to join the Healdsburg fault zone. This is a Holocene fault zone exhibiting highly distinctive fault–related topographic features, including sag ponds, scarps, benches, linear ridges and troughs, and numerous stream channels offset right laterally. Along most of its length, the fault zone is an array of several (sometimes as many as ten) distinct strands. A coincidence of earthquake epicenters also strongly suggests that the Rodgers Creek fault is indeed an active fault.

Data sources used for this fault are Fox and others (1973), Sims and others (1973), Blake and others (1974), Huffman (1971), and Armstrong (unpublished).

SAN ANDREAS FAULT

The San Andreas fault is concealed by the Pacific Ocean for half of its extent along the Sonoma County coastline. The northward trace of the fault zone can be observed on land at Bodega Bay, and from Fort Ross to Gualala.

Movement along the entire length of the visible portions of this fault within Sonoma County was recorded in 1906. All of the known and potentially active breaks have been delineated within an Alquist–Priolo Special Studies Zone.

Data from Blake and others (1971) were used to delineate the main fault traces. Some outlying and subsidiary traces are from Huffman (1972, 1973) and Koenig (1963).

TOLAY FAULT

The Tolay fault is concealed by San Pablo Bay to the south, where it has been projected by Koenig (1963) to the Hayward fault. To the north it has been projected by Koenig (1963) across Cotati Valley to connect with a fault offsetting Pliocene rocks. Fault related topographic features along the Tolay fault are less distinctive than those along the Rodgers Creek fault. However, several right–lateral offset streams and a large playa lake (Tolay Lake) suggest Pleistocene or later displacement. It is probable that the Tolay and Rodgers Creek fault zones are closely related, and photo and field evidence suggests that, to the south, a nearly continuous zone of fracture exists from one to the other.

Data sources used for the location of portions of this fault were Sims and others (1973), Blake and others (1974), and Koenig (1963). Field observations by Armstrong (1974) form the basis for the location of the remainder of the fault and for the conclusion that it is potentially or possibly active.

Possibly Active Faults

BLACK MOUNTAIN FAULT

Possible Quaternary movement on the Black Mountain fault is indicated on aerial photos by lineaments crossing Quaternary terrace alluvium and by relatively young–appearing ground disturbance along the trace in the vicinity of Maacama Creek.

DIANNA ROCK FAULT

McLaughlin (1974) mapped this fault and attributed Quaternary movement to it on the basis of Holocene terrace alluvium deformed against it (oral communication, 1975). In addition, Hamilton and Muffler (1972) recorded microearthquakes at The Geysers and concluded, "Most epicenters lie in a zone about 4 km long and 1 km wide passing through the *geothermal field* along a principal fault zone...A composite fault–plane solution indicates dextral strike–slip faulting on a NNW–striking plane subparallel with regional fault pattern." The fault shown may be the source of the microearthquake activity.

TOMBS CREEK FAULT

The Tombs Creek fault is an extension of the northernmost branch of the Porter Creek fault zone of Gealey (1951). Displacement of rock masses along it suggests right–lateral movement. The fault trace was identified northwest of the Healdsburg quadrangle by the alignment of saddles and canyons as seen on aerial photos. Right–lateral deflection of Osser Creek, Flat Ridge Creek, the Wheatfield Fork of the Gualala River, and Tombs Creek occurs at their intersections with the trace.

MT. JACKSON FAULT

Right–lateral displacements of rock units and streams are common along the Mt. Jackson fault. The Santa Rosa Sheet of the Geologic Map of California (Koenig, 1963) well illustrates the larger features, notably the offsets of "The Cedars" serpentine mass and of the Merced Formation near Forestville, and the right–lateral deflection of the Russian River. Systematic right–lateral stream deflections are present near Devils Creek.

The Mt. Jackson fault zone may be projected southward through the Laguna de Santa Rosa, and it is probable that the latter is related to the Mt. Jackson fault structure.

OTHER POSSIBLY ACTIVE FAULTS

Possibly active faults in Alexander Valley and southeast of Santa Rosa have been plotted from USGS data (Helley, 1970). Location of the fault in Alexander Valley was modified slightly on the basis of oral communications with Helley (1975). The faults also are shown at small scale and described in Borcherdt (1975, figure 3, table 1). Although described as faults with Quaternary displacement (Borcherdt, 1975, table 1), uncertainties in the data have led to their designation herein as possibly active, rather than potentially active.

TSUNAMI HAZARD

Tsunamis, miscalled tidal waves, are phenomena that commonly accompany large earthquakes around the margins of oceans in many parts of the world. The generation mechanism for a tsunami is a disturbance of the sea bottom, such as a dip–slip fault, a submarine volcanic upheaval, or a submarine landslide. Any one of these events is capable of instantaneously displacing a large enough volume of water to generate a sea wave capable of crossing an ocean several times.

At sea, the tsunami travels at speeds averaging 500 miles per hour, but is rarely observed because its wave height is usually less than 1 foot and wave length can be over 1 mile from crest to crest. However, upon reaching shallow water, a poorly understood and relatively unpredictable phenomenon called runup occurs. In shallow water the velocity slows, the wave length shortens, and the wave height increases. Factors affecting the size of the runup re the volume of water displaced at the origin, the distance from the origin, the orientation of the coast with respect to the wave's travel path, and the slope and irregularities of the offshore topography (Ritter and Dupre, 1972).

In Sonoma County the major tsunami hazard areas lie along the Pacific Coast and a minor hazard area exists along the border of San Pablo Bay. Plate 1B shows the area, as delineated by the U.S. Geological Survey (Ritter and Dupre, 1972), to be affected by a 200–year tsunami (i.e. a wave that would be equaled or exceeded on the average of once in 200 years). Plate 1A shows the area to be affected by a 200–year tsunami delineated by Huffman. For the most part, this is the same area that might be affected by winter sea storms, sea cliff erosion, and winter flooding (in the bay). These tsunami inundation maps are oversimplified due to the state–of–the–art and probably overstate the hazard in most places, but may fall short in depicting the severity of the freak runup that can occur locally in coves and inlets.

LANDSLIDES AND SLOPE STABILITY

A landslide is a mass "downward and outward movement of slope–forming materials composed of natural rock, soils, artificial fills, or combinations thereof" (Varnes, 1958, plate 1). Landslides may be classified according to type of movement and materials. Most landslides involve some combination of the above characteristics.

Recognition of Landslides

Landslides were recognized and mapped mainly by conventional techniques of aerial photographic interpretation of landforms. Characteristic topographic features result from landslide movement (see figure 7). Particularly useful indications of slide presence are scarps, benches, closed depressions and sag ponds. Such features are the product of differential movement within the slide, including distension and down–dropping of portions of the mass, rotation on arcuate surfaces of rupture, and bulging or ridging of slide materials moving out over stabler ground.

The possible landslide forms are numerous and varied and include slabs, wedges, blocks, fans, and irregular sheets. They are dependent on many factors, particularly type of movement, materials, and age. As landslides move downward and outward, a depression and extension of gross form occurs, sometimes deflecting a stream outward from the slide at the toe. An amphitheater–like feature may be formed, with an arcuate headwall scarp. Most mud flows are long sinuous "tongues" reflecting great mobility. Control by bedrock structures often produces forms characterized by linear elements.

Other erosion processes work to obliterate the characteristic landslide topography, and with the cessation of movement and passage of time many slides become difficult to identify with confidence, wholly or in part. Many of the possible landslides mapped on Plates 2A and 2B probably are old landslides of this nature.

Landslide Types in Sonoma County

Landslides mapped on Plates 2A and 2B vary in size, age, type of materials, rate and type of movement, and degree of surface expression. Limitations to time and techniques permitted only a differentiation in size and degree of confidence of recognition. However, a considerable amount is known or reasonably inferred about their characteristics based on limited field inspections, prior investigations (Huffman, 1971, 1972, 1973), case histories of damaging landslides, and knowledge of the general characteristics of landslides in the north Coast Ranges.

Landslides range in size to over 2 miles in longest dimension. Such large slides are exemplified by one that is located 2 miles northwest of Mt. St. Helena, dissected by Mill Stream. This landslide and many others are apparently Pleistocene slumps containing much intact bedrock which has moved over surfaces of rupture possibly 500 feet in maximum depth below the ground surface. It is likely that these are presently static. However, numerous recently active landslides occur locally as landslides within landslides because of the weak Pleistocene slide materials.

Materials range from fluid soil in mud flows (as noted, for example, along Yellowjacket Creek at Knights Valley)

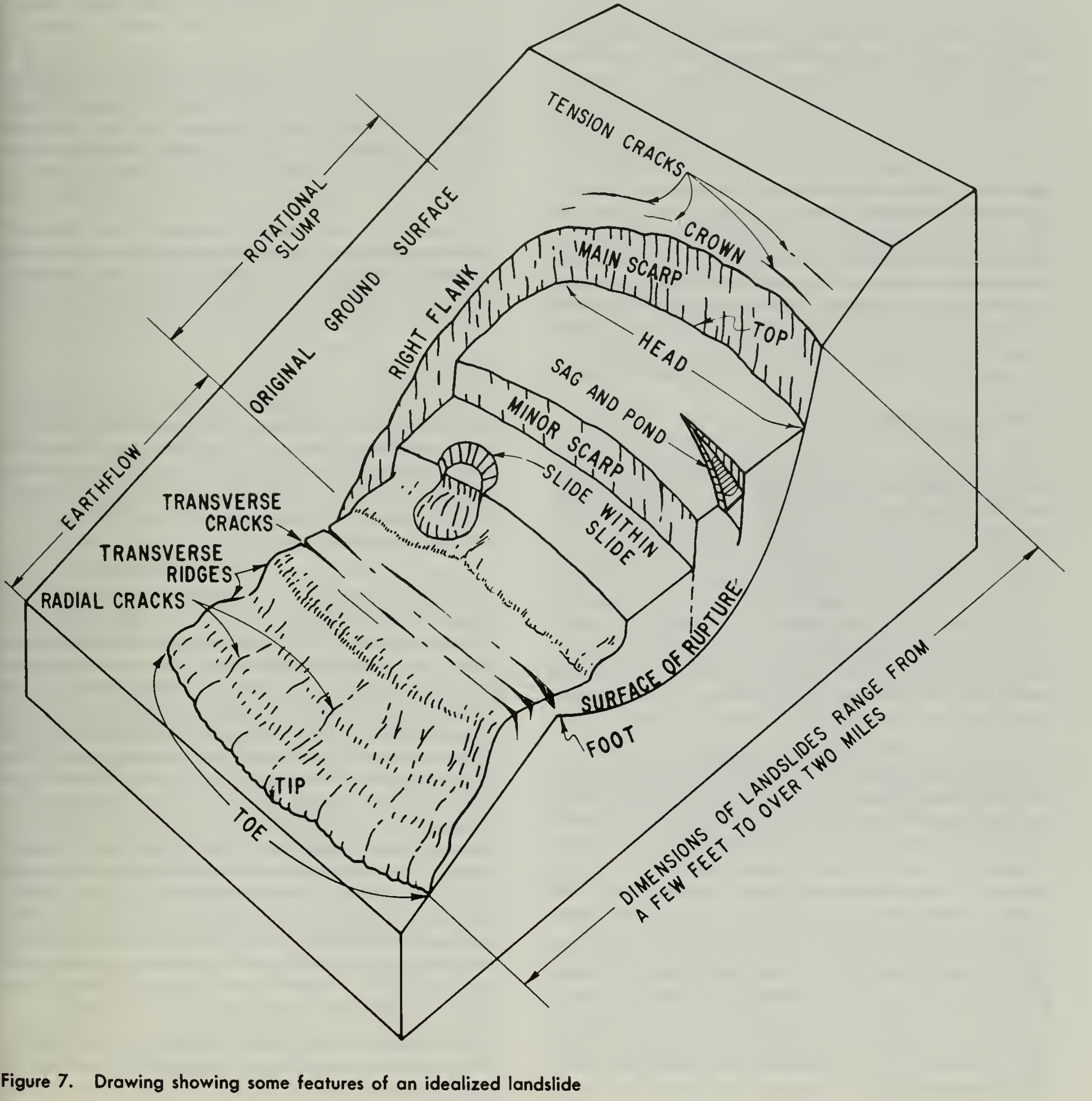

Figure 7. Drawing showing some features of an idealized landslide

to extensive, intact masses of volcanic rock in large Pleistocene landslides. Similarly, modes of movement include flow, rock fall, and rapid avalanche–type movement triggered by earthquakes (see below). However, by far the greater portion of the landslides contain soil and broken rock, which move slowly and recurrently over a basal slide zone in response to high–intensity, long–duration rainfall.

Causes of Landslides

Landslides occur when the strength of the slope–forming materials is exceeded by the stresses acting upon them. This relationship is used in soil mechanic investigations to calculate a factor of safety against sliding: FS = shearing strength/shearing stresses. When the factor is significantly greater than one, the slope is considered stable; when the factor is one or less than one, failure and sliding are imminent. Shearing strength parameters are the cohesion and angle of internal friction of the materials. Shearing stress is essentially the component of the weight of the potential slide mass acting in a downhill direction parallel to a potential failure plane. Moisture content of the soil is an important variable: high moisture contents greatly reduce soil shear strength. Determination of the shear strength parameters through laboratory testing and the geometry of the slide mass by subsurface exploration permit calculation of the factor of safety at specific sites.

GEOLOGIC MATERIALS

Geologic properties, structure, and history influence the strength of slope–forming materials. For example, *montmorillonite* and related clays have a great capacity to adsorb water, which reduces the shear strength to low values. Such clays are found abundantly in the landslide–prone Petaluma Formation and portions of the Sonoma Group (plates 2A and 2B). In the latter, they are derived from *tuffs* and *tuffaceous* sediments. Clays of this derivation were major components in the slide zones underlying the Mendocino Avenue landslide of 1955–56 ("Moving Mountain") which destroyed five homes (Woodward–Clyde–Sherard and Associates, 1965, p. 13, 21).

Adversely oriented planes of weakness, such as bedding, faults, and fractures, are potential zones along which the overlying material may separate and slide. Layered strata dipping parallel to the slope are particularly subject to movement as illustrated by the Maacama Creek slide, triggered by the 1906 earthquake (see below: Earthquakes). Cuts at the bases of slopes, produced by stream erosion or man, often induce sliding on such weak zones.

Fault zones contain weak rock, crushed and broken by repeated fault movements. This undoubtedly has contributed to extensive natural landsliding in the Healdsburg fault zone east of Healdsburg. This region was mapped in large part as an area of landslides by Gealey (1951). Numerous houses and roads have been damaged by landslide movement there.

Extensive large Pleistocene landslides, containing broken and fractured rock, mantle many slopes. Because their size surpasses that of modern active landslides, it is inferred that they formed under different conditions — probably higher rainfall during glacial intervals, possibly coupled with greater tectonic activity. These slides are being incised and dissected by streams which trigger extensive renewed movement along ancient shear zones and surfaces of rupture. A subdivision in the Sonoma Mountains is located on a complex of Pleistocene and Holocene landslides which have contributed to the damaging sliding there (Cooper–Clark and Associates, 1974).

NATURAL PROCESSES

Geologic and other natural processes alter slope stability. Heavy rainfall saturates the slopes, reducing the shear strength of materials and inducing landslides and *soil creep.* High flood stages erode stream banks and cause slumps. These movements lower the stability of upslope areas by removing support at the foot of potential slides.

Chemical and mechanical weathering break down and weaken soil and rock materials. High ground water levels and water concentrations at seepages and springs adversely affect stability and are commonly associated with landslides.

Earthquakes

Earthquakes may induce landsliding through liquefaction or by triggering movement in slopes already near the limit of stability. Numerous landslides occurred in Sonoma County during the April 18, 1906, earthquake and were mentioned in the Report of the California Earthquake Commission (Lawson and others, 1908). Excerpts from this report are quoted below.

Maacama slide, 6 miles east of Healdsburg (p. 184; report by R.S. Holway). — "This slide is on the north side of a ridge that runs in an easterly direction and that is at this point from 225 to 300 feet above the bed of Maacama Creek, which runs along the foot of the north slope. Mr. Hugh Simpson, whose house is just beyond the foot of the slide, states that the entire slide took place at the instant of the earthquake. The slide is about 0.125 mile wide at the top and about 0.5 mile long. The rock is a very light, porous, volcanic tuff and seems to be free from water. A slicken–sided wall on the east shows a very smooth surface in spite of the soft rock. Striae near the top run N. 13 degrees W. with a pitch of about 24 degrees. The slide seems to have taken off some of the ridge; that is, it started a few feet down the south slope of the ridge, cut its way through a fir forest and dammed Maacama Creek with rocks and trees. Either two successive slides occurred or else the upper part of the moving mass was arrested part way down, for a bank with the vegetation of the top rests across the slide about one–third of the way down."

This slide was subsequently visited by G.K. Gilbert, who contributes the following supplementary note (p. 184 –185):

"At Maacama schoolhouse, I saw the large landslide described by Professor Holway. The rocks involved are in layers, with a dip of about 30 degrees in the direction of the slide. It is therefore probable that the slide was partly determined by the dip, though it seems to have been further determined by the erosion of the valley of Maacama Creek. The shock at the point was notably strong."

Vicinity of Santa Rosa (p. 203; report by Drury Butler).—"Near the top of Taylor Hill, in a marshy place, there was a landslide, the earth having slide [slid] on a clayey bottom ... at the [Sonoma County] hospital a marshy place along the creek slipped toward the creek and the flow of springs was greatly increased."

Sebastopol, Sonoma County (p. 205; report by G.K. Gilbert).—"On the [Luther] Burbank farm a small landslide occurred, a layer of moist soil only a few feet in thickness moving down the slope, introducing bends in various lines of cultivated plants. I saw another feature of this sort on an adjacent farm and was told of others which I did not visit."

Valley Ford, Sonoma County (p. 199; report by R.S. Holway).—"A landslide of several hundred yards in length but of very slight movement is found on the side of the valley directly east of town. The slide has moved just enough to make a furrow–like ridge on the lower side and has developed cracks on the upper side."

Stewarts Point, Sonoma County (p. 180–181).—"On both sides of the sharp bend of the [South Fork of the Gualala] river east of the two bridges are extensive landslides, making a clean sweep down the mountain side. The slide on the north side completely blocked the wagon road and was being removed at the time of the visit (May 12). It is of such a height and steepness as to menace the road at this point with renewed sliding in the future, especially during wet weather.

"Gualala Valley. At Casey's ranch, half a mile west of the fault, the destruction was notably severe, one building having entirely collapsed, and the dwelling–house having been badly strained by the shock. The ranch stands on the east edge of the ridge, west of the Gualala River, and the fault runs along the mountain side several hundred feet below it. The slope is a steep one, densely timbered except for its upper portion. Landslides were found over a large part of its surface, but only in a few isolated spots had they resulted in the complete removal of the original surface and the forest growing thereon; so that a view from across the river revealed no appreciable changes in the landscape. The slopes east of the river were similarly affected and the fallen timber produced a tangle not unlike that of extensive windfalls. In at least two places the river was temporarily dammed up by slides from both slopes meeting in the stream bed, but none of these dams was of noteworthy size."

Timber Cove, Sonoma County (p. 181).—"In the bluffs along the coast and in the numerous rock cuts along the wagon road, the rocks appeared loosened up, many old fissures having opened and left the rock masses in more or less unstable positions. Landslides, in rocky as well as in loose material, have occurred in a great number of places, though none were at all extensive."

Fort Ross to Bodega Head.—An examination of the coast between Fort Ross and Bodega Head was made by Professor J.N. LeConte and Mr. A.C. Wright. The portion of their report dealing with the distribution of intensity follows (p. 190–191):

"From Fort Ross the line of the earthquake fissure was followed south to the point where it passes into the sea. From this point we followed the beach for 8 miles. Several slides were seen about 3 miles south of the Fort. One of these was of great size, being between 300 and 400 feet in height. These are evidently old slides, and the amount of material brought down y the recent earthquake, though large, is insignificant compared with the size of the scar."

MAN'S ACTIVITIES

Man's activities may adversely affect stability, depending on the nature, design, construction, and maintenance of the work. In particular, cuts may remove support at the toe of slopes, thus precipitating movement. Septic systems and diversions of surface runoff concentrate moisture in the soil, lowering the strength of materials, and promoting instability.

SLOPE INCLINATION

On steeper slopes, a greater component of the weight of the soil and rock mass acts in a downslope direction parallel to any potential failure plane. Hence, they commonly are regarded as indicating a greater potential instability. However, since slope stability is a function of numerous factors, this simple relationship can be seriously misleading. Landslide movement brings materials to lower topographic elevations and inclinations. Landslides, however, are the least stable terrain, hence the real stability of any area may be directly the converse of that implied by the slope assumption. Very steep slopes may exist because the underlying rocks are resistant to landsliding and other forms of erosion; gentle slopes may exist because the underlying rocks are not resistant to erosion.

The above considerations have particular relevance to planners involved with zoning dwelling–unit densities on the basis of slope inclinations alone. It is possible that allocation of higher densities to low slope areas will increase the risks from slope instability and landsliding.

TIME

Natural processes work through time to cause cumulative small re–adjustments in the stability of slopes. As a result, areas of lowest stability may become unstable and slide during the useful life of structures on them. Such a condition is exemplified by the Los Alamos Road landslide, which destroyed a house and part of the County road. The slide is within a much larger area of an apparently static Pleistocene landslide. The house was inhabited for nearly thirty years, reportedly without a sign of movement prior to sliding in early 1974 (Santa Rosa Press Democrat, March 12, 1974).

It has been found that soils will deform or creep at stresses below those sufficient to overcome the shear strength and cause immediate failure. Singh and Mitchell (1969) developed a parameter to determine the time dependency of creep in various soils. It was found that soils containing significant montmorillonite clay are prone to creep until rupture occurs under conditions of sub–failure stress levels. Other soils become stronger with time and creep rupture in these is unlikely. Such time–dependent creep may explain the failure of some slopes which seemingly have been stable for many years.

Events which greatly lower stability, such as earthquakes and extremely heavy precipitation, occur infrequently. However, as the elapsed time since the last event increases, the time remaining before the next event decreases.

Cumulative effects of man's activities, such as increased water concentrations in the soil from septic systems and surface diversions, become more pronounced with time, and the chances of the adverse conjunction of natural and man–made events become greater.

The time intervals alluded to are no greater than the anticipated useful life of many structures. Consequently, the apparent stability of some hillside developments in geologically questionable environments is deceptive. Many such developments have taken place in Sonoma County without adequate geologic control. Numerous damaging slides have occurred and it is to be expected that they will continue in increasing numbers because of the cumulative effects of destabilizing processes in older developments.

PROXIMATE AND CONTRIBUTING CAUSES

Natural and man–induced landslides have multiple causes. An event may trigger movement in slopes reduced to low stability by a combination of factors. The underlying factors must be recognized in order to achieve a correct and lasting solution. Also, a damaging landslide may be the first signal that more extensive underlying unstable conditions exist.

Exemplifying these relationships is the Maacamas slide which was triggered by the April 18, 1906, earthquake – the proximate cause. Contributing causes were the weak materials, downslope inclination of bedding, and undercutting of the slope by Maacamas Creek. Such factors can be mapped and interpreted during geologic studies for planning and development.

Slope Stability Evaluation

The slope stability evaluation is a broad–scale interpretation of the landsliding susceptibility of rock and soil underlying slopes. It establishes five categories of relative stability based on the presence of landslides, characteristics of materials inferred from the geologic units, and slope inclination. Distribution of the geologic units was derived from Plates 3A and 3B. Slope inclinations were taken from U.S. Geological Survey slope maps developed for the San Francisco Bay Region Environment and Resources Planning Study (in cooperation with the U.S. Department of Housing and Urban Development).

CATEGORIES OF STABILITY

Landslides are assigned the lowest stability (hence, highest hazard) rating for several reasons. Some landslides are presently unstable and move slowly down–slope periodically, often annually, as a result of heavy seasonal rainfall; many are static but have slid to rest at the limits of stability. Therefore, very slight natural or man–made disturbances may generate movement. Many older landslides may be stabilized regionally but are locally unstable. The landslides contain sheared, weakened materials, and when surface and subsurface drainage have been disrupted, water is concentrated at sag ponds and seepages. Stream erosion of these terrains has created steep canyon slopes exposing unstable slide debris and triggering extensive local landsliding.

For these reasons all landslides, regardless of apparent character, have been assigned to the lowest stability category. Similarly, possible landslides received the lowest stability designation.

C areas are zones of relatively unstable rock and soil on slopes greater than 15 percent containing abundant landslides. Relative instability is inferred primarily from the abundant mapped landslides and secondarily from the description of geologic units (plates 3A and 3B) and knowledge of their characteristics. Abundant landslides are inferred to reflect underlying rock and soil conditions conducive to instability. Although most geologic units contain sufficient landslides to be in this category, significant variations exist because of their heterogeneity. Hence, there is no detailed correlation between slope stability and mapped geologic units.

B areas are zones of relatively stable rock and soil on slopes greater than 15 percent containing few landslides. The more stable geologic units include the sedimentary and igneous rocks west of the San Andreas fault, conglomerate of the Great Valley Sequence, and portions of the Franciscan Group and Merced Formation.

Bf areas are locally level areas within hilly terrain. Slopes are generally less than 15 percent. They may be underlain or bounded by unstable or potentially unstable rock materials. They include, for example, coastal terraces which are bounded by the actively eroding sea cliff.

A areas are zones of greatest relative stability under non–earthquake conditions. Slopes are dominantly less than 15 percent. Many of these areas are basins of deposition — valleys and plains subject to flooding and siltation. Hence, they are radically different geologic environments from adjacent eroding hills. However, earthquake ground shaking may induce liquefaction accompanied by landslides on slopes of very low inclination. Because **A** areas are primarily zones of unconsolidated materials and high water table, they are particularly susceptible to the earthquake-induced sliding discussed in the section "Seismicity, ground shaking, and liquefaction". Additionally, bank slumping has damaged numerous structures placed too close to streams in these areas in Sonoma County.

Categories are interpretive and apply generally to large areas. Within each area, conditions may range in detail through all four stability categories. Hence, an **A** area may locally contain unmapped landslides, and a landslide area may contain stable slopes of slight inclination. For these reasons, and because of the hazard of earthquake–induced landsliding, site geologic studies are recommended in some **A** areas also.

GLOSSARY OF SELECTED GEOLOGIC TERMS

AGGRADING RIVER – A river which is raising the surface over which it flows by net deposition of sediment.

ALLUVIAL – Referring to alluvium, an unconsolidated earth material transported and deposited by running water.

AQUIFER – A subsurface zone capable of producing water, as from a well.

BASEMENT – The deepest regional rock complex within the earth's crust, upon which a series of younger rocks have been deposited.

BEDROCK – The consolidated rock deposit closest to the earth's surface at any location.

CRUSTAL – Pertaining to the upper rigid portion of the earth (the upper 5 to 70 km).

DIFFERENTIAL SETTLEMENT – The uneven subsidence of earth materials (as occurs during ground shaking).

EN ECHELON – In a parallel, offset, step–like pattern (commonly used in reference to faults).

EPICENTER – A point on the earth's surface directly above the focus of an earthquake.

FAULT CREEP – Slow, spasmodic displacement along a fault trace unaccompanied by earthquakes.

FLUID INJECTION WELL – A well used for the disposal of fluids below the earth's surface.

FREE FIELD – Refers to the placement of an instrument in such a location so as not to be affected by the works of man.

FREQUENCY (of an earthquake) – The rate of earth shaking in cycles per second.

GEOMORPHIC – Pertaining to the form of the physical features of the earth's surface.

GEOPHYSICAL SURVEY – Exploration of the earth by measurement of its physical properties (i.e. magnetic, electrical, seismic).

GEOTHERMAL FIELD – A locality where energy is extracted from the earth's subsurface in the form of hot water or steam.

GLACIAL – Pertaining to moving ice sheets, as covered large portions of the continents during the Pleistocene Epoch.

INTERGLACIAL – Pertaining to the time periods between advances of the continental ice sheets of the Pleistocene Epoch.

LASER INSTRUMENTATION SURVEY – The use of a monochromatic (single wave length) light source to precisely measure the travel time of light between two points in order to obtain very accurate measurements of distance.

LURCH CRACKING – A phenomenon associated with ground shaking whereby portions of the ground are heaved upward.

MECHANICAL WEATHERING – The wearing away of earth materials by the physical action of water, wind, or ice.

MONTMORILLONITE – A group of clay minerals that swell after absorbing water.

PLIO–PLEISTOCENE – Spanning portions of both the Pliocene and Pleistocene epochs.

PORE–WATER PRESSURE – The water pressure acting between the grains at any point within an earth material.

RIGHT LATERAL – The apparent movement along a strike–slip fault where, when looking across the surface trace of the fault, features on the opposite side appear to have moved to the right.

SALTWATER INTRUSION – The migration of salt water into a fresh–water aquifer (usually the result of over–draughting of water wells).

SEISMIC – Pertaining to or produced by earthquake vibrations.

SEISMICITY – Earthquake activity.

SLICKENSIDE – An earth or rock surface polished or scratched by friction along a fault plane or other zone of movement.

SOIL CREEP – The slow episodic movement of unconsolidated earth materials.

SPREADING (sea floor) – The lateral movement of the sea floor away from a central spreading zone (plate tectonics theory).

STRAIN (crustal, fault) – Deformation of the earth's crust by tectonic forces.

STRIAE – Scratches in the surface of an earth material resulting from erosion movement.

STRONG MOTION INSTRUMENT – An instrument, such as accelerograph, seismograph, or free field strong motion seismograph, for measuring relative ground motion during an earthquake and triggered to record at a pre–determined minimum ground acceleration.

TECTONIC (force) – Pertaining to the crustal forces responsible for faulting, folding, sea floor spreading, and the general shaping of continents.

TERRACE – A nearly flat platform formed by erosion and/or deposition by a river, sea, or lake.

TRACE (fault) – The line formed by the intersection of a fault plane with the earth's surface.

TUFF (tuffaceous) – A rock formed by the compaction of small volcanic fragments (less than 4 mm in diameter).

YOUNGER BAY MUD – The most recent (12,000 years to present) of the unconsolidated San Francisco Bay deposits of clay, silt, and sand.

REFERENCES CITED

Addicott, W.O., 1968, Mid-Tertiary zoogeographic and paleogeographic discontinuities across the San Andreas fault, California, *in* Dickinson, W.R., and Grantz, Arthur, editors, Proceedings of the conference on geologic problems of the San Andreas fault system: Stanford University Publications, Geological Sciences, v. 11, p. 144–165.

Alfors, J.T., Burnett, J.L., and Gay, T.E., Jr., 1973, Urban geology master plan for California: California Division of Mines and Geology Bulletin 198, 112 p.

Algermissen, S.T., Stepp, J.C., Reinhart, W.A., and Arnold, E.P., 1969, Studies in seismicity and earthquake damage statistics, 1969, Appendix B: U.S. Department of Commerce, Environmental Science Services Administration, Coast and Geodetic Survey.

Armstrong, C.F., 1974, Unpublished active fault mapping in parts of the Glen Ellen, Petaluma River, and Sears Point 7½–minute quadrangles, California: California Division of Mines and Geology.

Barosh, P.J., 1969, Use of seismic intensity data to predict the effects of earthquakes and underground nuclear explosions in various geologic settings: U.S. Geological Survey Bulletin 1279, 93 p.

Blake, M.C., Jr., Smith, J.T., Wentworth, C.M., and Wright, R.H., 1971, Preliminary geologic map of western Sonoma County and northernmost Marin County, California: U.S. Geological Survey and U.S. Department of Housing and Urban Development, Basic Data Contribution 12, San Francisco Bay Region Environment and Resources Planning Study – 1:62,500.

Blake, M.C., Jr., Bartow, J.A., Frizzell, V.A., Jr., Schlocker, J., Sorg, D., Wentworth, C.M., and Wright, R.H., 1974, Preliminary geologic map of Marin and San Francisco Counties and parts of Alameda, Contra Costa, and Sonoma Counties, California: U.S. Geological Survey and U.S. Department of Housing and Urban Development, Basic Data Contribution 64, San Francisco Bay Region Environment and Resources Planning Study – 1:62,500.

Bonilla, M.G., 1970, Surface faulting and related effects, *in* Wiegel, R.L., editor, Earthquake engineering: Prentice Hall, Englewood Cliffs, New Jersey, p. 47–74.

Borcherdt, R.D., editor, 1975, Studies for seismic zonation of the San Francisco Bay region: U.S. Geological Survey Professional Paper 941–A, 102 p.

Brown, R.D., Jr., and Wolfe, E.W., 1972, Map showing active breaks along the San Andreas fault between Point Delgado and Bolinas Bay, California: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-692.

Cardwell, G.T., 1958, Geology and ground water in the Santa Rosa and Petaluma Valley areas, Sonoma County, California: U.S. Geological Survey Water Supply Paper 1427, 273 p.

Clark, M.M., 1971, Map showing recently active breaks along the Garlock and associated faults, California: U.S. Geological Survey Miscellaneous Geological Investigations Map I–741 – 1:24,000.

Clark, W.B., and Hauge, C.J., 1971, When the earth quakes – you can reduce the danger: California Division of Mines and Geology, California Geology, v. 24, no. 11, p. 203–216.

Cloud, W.K., 1970, The Santa Rosa earthquake of October 1969: California Division of Mines and Geology, Mineral Information Service, v. 23, no. 3, p. 43–63.

Coffman, J.L., and van Hake, C.A., 1973, Earthquake history of the United States, [revised edition through 1970]: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, 208 p.

Dickinson, W.R., and Grantz, Arthur, 1968, Indicated cumulative offsets along the San Andreas fault in the California Coast Ranges, *in* Dickinson, W.R., and Grantz, Arthur, editors, Proceedings of the conference on geologic problems of the San Andreas fault system: Stanford University Publications, Geological Sciences, v. 11, p. 117–120.

Dwyer, M.J., 1974, Landslide investigation, Diamond "A" Subdivision, Sonoma County, California [for the County of Sonoma]: Cooper–Clark and Associates.

Eckel, E.B., 1958, Landslides and engineering practice: Highway Research Board Special Report 29, Washington, D.C., 232 p.

Evernden, J.F., and James, G.T., 1964, Potassium–argon dates and the Tertiary floras of North America: American Journal of Science, v. 262, no. 8, p. 945–974.

Fox, K.F., Jr., Sims, J.D., Bartow, J.A., and Helley, E.J., 1973, Preliminary geologic map of eastern Sonoma County and western Napa County, California: U.S. Geological Survey and U.S. Department of Housing and Urban Development, Basic Data Contribution 56, San Francisco Bay Region Environment and Resources Planning Study – 1:62,500.

Frenaye, T., 1974, Active landsliding field observations: unpublished mapping – 1:24,000.

Frizzell, V.A., Jr., 1974, Reconnaissance photointerpretation map of landslides in parts of the Hopland, Kelseyville, and Lower Lake 15–minute quadrangles, Sonoma County, California: U.S. Geological Survey and U.S. Department of Housing and Urban Development, Basic Data Contribution 66, San Francisco Bay Region Environment and Resources Planning Study – 1:62,500.

Gealey, W.K., 1951, Geology of the Healdsburg quadrangle, California: California Division of Mines Bulletin 161, 76 p.

Gibbs, J.F., and Eaton, J.P., 1971, A digitized map of seismic ground response of the San Francisco Bay region, California: U.S. Geological Survey open-file map.

Greensfelder, R.W., 1972, Crustal movement investigations in California: California Division of Mines and Geology Special Publication 37, 35 p.

Hamilton, R.M., and Muffler, L.J.P., 1972, Microearthquakes at The Geysers geothermal area, California: Journal of Geophysical Research, v. 77, no. 11, p. 2081–2086.

Helley, E.J., 1970, Map showing Quaternary fault activity in the Bay Area: unpublished mapping.

Higgins, C.G., Jr., 1952, Lower course of the Russian River, California: University of California Publications in the Geological Sciences, v. 29, no. 5, p. 181–264.

Housner, W., 1970, Strong ground motion, *in* Wiegel, R.L., editor, Earthquake engineering: Prentice Hall, Englewood Cliffs, New Jersey, p. 75–92.

Hsu, K.J., 1969, Preliminary report and geologic guide to Franciscan melanges of the Morro Bay–San Simeon area, California: California Division of Mines and Geology Special Publication 35, 46 p.

Huffman, M.E., 1971, Geology for planning in the Sonoma Mountains and Mark West–Riebli Road areas, Sonoma County, California: California Division of Mines and Geology Open–file Report 72–25 – 1:24,000.

Huffman, M.E., 1972, Geology for planning on the Sonoma County coast between the Russian and Gualala Rivers: California Division of Mines and Geology Preliminary Report 16 – 1:24,000.

Huffman, M.E., 1973, Geology for planning on the Sonoma County coast between the Russian River and Estero Americano: California Division of Mines and Geology Preliminary Report 20 – 1:24,000.

Jennings, C.W., 1970, Unpublished geologic map of the NW ¼ of the Santa Rosa 7½–minute quadrangle, California: California Division of Mines and Geology – 1:12,000.

Jennings, C.W., 1973, California preliminary fault and geologic map: California Division of Mines and Geology Preliminary Report 13 – 1:750,000.

Koenig, J.B., 1963, The geologic setting of Bodega Head: California Division of Mines and Geology, Mineral Information Service, v. 16, no. 7, p. 1–10.

Koenig, J.B., 1963, Santa Rosa sheet: California Division of Mines and Geology, Geologic Map of California – 1:250,000.

Kunkel, F., and Upson, J.E., 1960, Geology and ground water in Napa and Sonoma Valleys, Napa and Sonoma Counties, California: U.S. Geological Survey Water Supply Paper 1495, 252 p.

Lawson, A.C., and others, 1908, The California earthquake of April 18, 1906, Report of the State Earthquake Investigation Commission: Carnegie Institution of Washington Publication 87, v. 3, atlas.

McClure, E., 1973, Performance of single–family dwellings in the San Fernando earthquake of February 9, 1971: U.S. Department of Housing and Urban Development and National Oceanic and Atmospheric Administration.

McLaughlin, R.J., 1974, Preliminary geologic map of The Geysers steam field and vicinity, Sonoma County, California: U.S. Geological Survey open-file map 74–238 – 1:24,000.

McNitt, J.R., 1968, Geology of the Kelseyville quadrangle, Mendocino, Lake, and Sonoma Counties, California: California Division of Mines and Geology Map Sheet 9 – 1:62,500.

Meade, B.K., and Small, J.B., 1966, Current and recent movement on the San Andreas fault; *in* Bailey, E.H., editor, Geology of northern California: California Division of Mines and Geology Bulletin 190, p. 385–391.

Miller, R.W., 1967, Results of triangulations for earth movement study at California aqueduct fault–crossing sites: National Ocean Survey office report, 11 p.

Miller, R.W., 1970, Results of surveys for study of earth movement, 1876, 1906, and 1969 – vicinity of Fort Ross, California: National Ocean Survey office report, 19 p.

Morton, D.M., 1973, Unpublished landslide mapping by aerial photo interpretation in the Arched Rock, Duncan Mills, Camp Meeker, Sebastopol, and Two Rock 7½-minute quadrangles, California: U.S. Geological Survey.

Nason, R.D., 1971, Shattered earth at Wallaby Street, Sylmar; *in* The San Fernando earthquake of February 9, 1971: U.S. Geological Survey Professional Paper 733, p. 97–98.

Oakeshott, G.B., editor, 1975, San Fernando, California, earthquake of 9 February 1971: California Division of Mines and Geology Bulletin 196, 463 p.

Rice, S.J., 1973, Geology and geologic hazards of the Novato area, Marin County, California: California Division of Mines and Geology Preliminary Report 21, 47 p.

Richter, C.F., 1958, Elementary seismology: W.H. Freeman and Company, San Francisco, California, and London, England, 768 p.

Richter, C.F., 1959, Seismic regionalization: Seismological Society of America Bulletin, v. 49, no. 2, p. 123–162.

Ritter, J.E., and Dupré, W.E., 1972, Map showing areas of potential inundation by tsunamis in the San Francisco Bay region, California: U.S. Geological Survey and U.S. Department of Housing and Urban Development, Basic Data Contribution 52, San Francisco Bay Region Environment and Resources Planning Study – 1:62,500.

Rogers, T.H., 1969, An active fault in the City of Hollister: California Division of Mines and Geology, Mineral Information Service, v. 22, no. 10, p. 159–164.

Ryall, A., Slemmons, D.B., and Gedney, D., 1966, Seismicity, tectonism, and surface faulting in the western United States during historic time: Seismological Society of America Bulletin, v. 56, no. 5, p. 1105–1135.

Schnabel, P.B., and Seed, H., 1973, Accelerations in rock for earthquakes in the western United States: Seismological Society of America Bulletin, v. 63, no. 2, p. 501–516.

Seed, H.B., and Schnabel, P.B., 1972, Soil and geologic effects on site response during earthquakes, *in* Proceedings of the International Conference on Microzonation for Safer Construction Research and Application, p. 61–86.

Sickles, J.M., 1973, Geology and geologic hazards of the Kenwood–Glen Ellen area, eastern Sonoma County, California: Unpublished Masters thesis, University of California, Davis, California.

Sims, J.D., Fox, K.F., Jr., Bartow, J.A., and Helley, E.J., 1973, Preliminary geologic map of Solano County and parts of Napa, Contra Costa, Marin and Yolo Counties, California: U.S. Geological Survey and U.S. Department of Housing and Urban Development, Basic Data Contribution 54, San Francisco Bay Region Environment and Resources Planning Study – 1:62,500.

Singh, A., and Mitchell, K., 1969, Creep potential and creep rupture of soils: International Conference on Soil Mechanics and Foundation Engineering, Mexico City, Mexico, Proceedings VII, p. 379–384.

Sonoma County Planning Department, Advanced Planning Division, 1974, Sonoma County General Plan Bulletin – Goals and Policies.

Steinbrugge, K.V., Cloud, K., and Scott, N.H., 1970, The Santa Rosa, California, earthquakes of October 1, 1969: Environmental Science Services Administration and Coast and Geodetic Survey, 99 p.

U.S. Army Corps of Engineers, 1965, Report on floods of December 1964 in northern California coastal streams: U.S. Army Corps of Engineers, San Francisco District, v. 111.

U.S. Geological Survey, Flood–prone areas in the Russian River drainage basin, Sonoma County, California: U.S. Geological Survey and U.S. Department of Housing and Urban Development, Basic Data Contribution 18.

U.S. Geological Survey, Flood–prone areas in the Petaluma River drainage basin and Cotati vicinity, Sonoma and Marin Counties, California: U.S. Geological Survey and U.S. Department of Housing and Urban Development, Basic Data Contribution 17.

Varnes, D.J., 1958, Landslide types and processes, *in* Highway Research Board Special Report 29, Landslides and engineering practice: National Academy of Sciences, National Research Council Publication 544, 232 p.

Wallace, R.E., 1970, Earthquake recurrence intervals on the San Andreas fault: Geological Society of America Bulletin, v. 81, no. 10, p. 2875–2890.

Wentworth, C.M., 1972a, Unpublished landslide mapping by aerial photo interpretation in the Petaluma, Petaluma River and Point Reyes Northeast 7½–minute quadrangles, California: U.S. Geological Survey.

Wentworth, C.M., 1972b, Unpublished landslide mapping by photo interpretation in the Healdsburg 15–minute quadrangle, California: U.S. Geological Survey.

Woodward–Clyde–Sherard and Associates, 1965, Soil investigation of the Mendocino Avenue Slide, Santa Rosa, California: City of Santa Rosa, Report for the City Engineer, 34 p.

Youd, T.L., and others, 1973, Liquefaction potential of unconsolidated sediments in the southern San Francisco Bay region, California: U.S. Geological Survey Open–file Report, 23 p.

Youd, T.L., 1973, Liquefaction, flow, and associated ground failure: U.S. Geological Survey Circular 688, 12 p.

Youd, T.L., and Olsen, H.W., 1971, Damage to constructed works associated with soil movements and foundation failures, *in* The San Fernando earthquake of February 9, 1971: U.S. Geological Survey Bulletin 733, p. 126–132.

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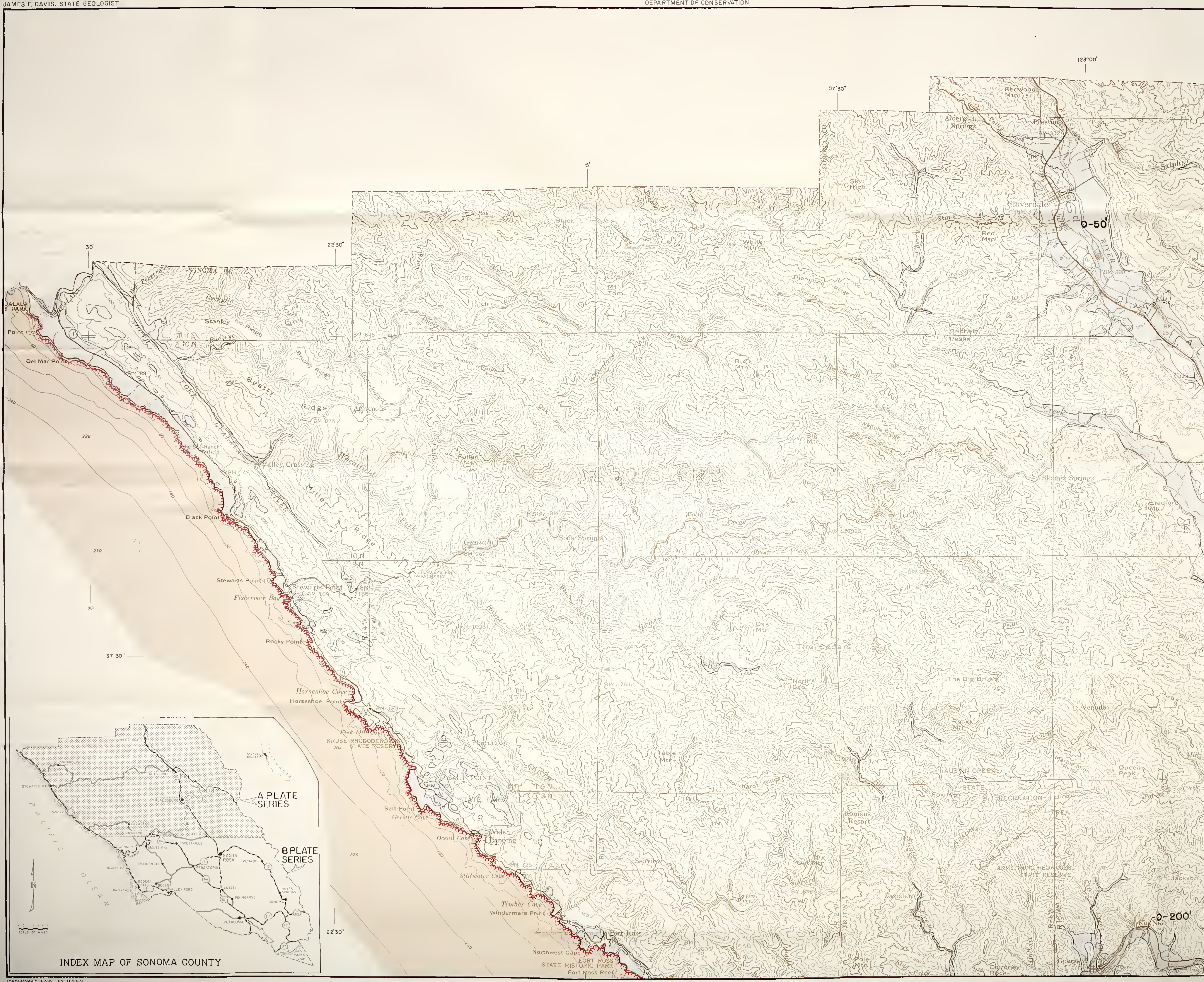

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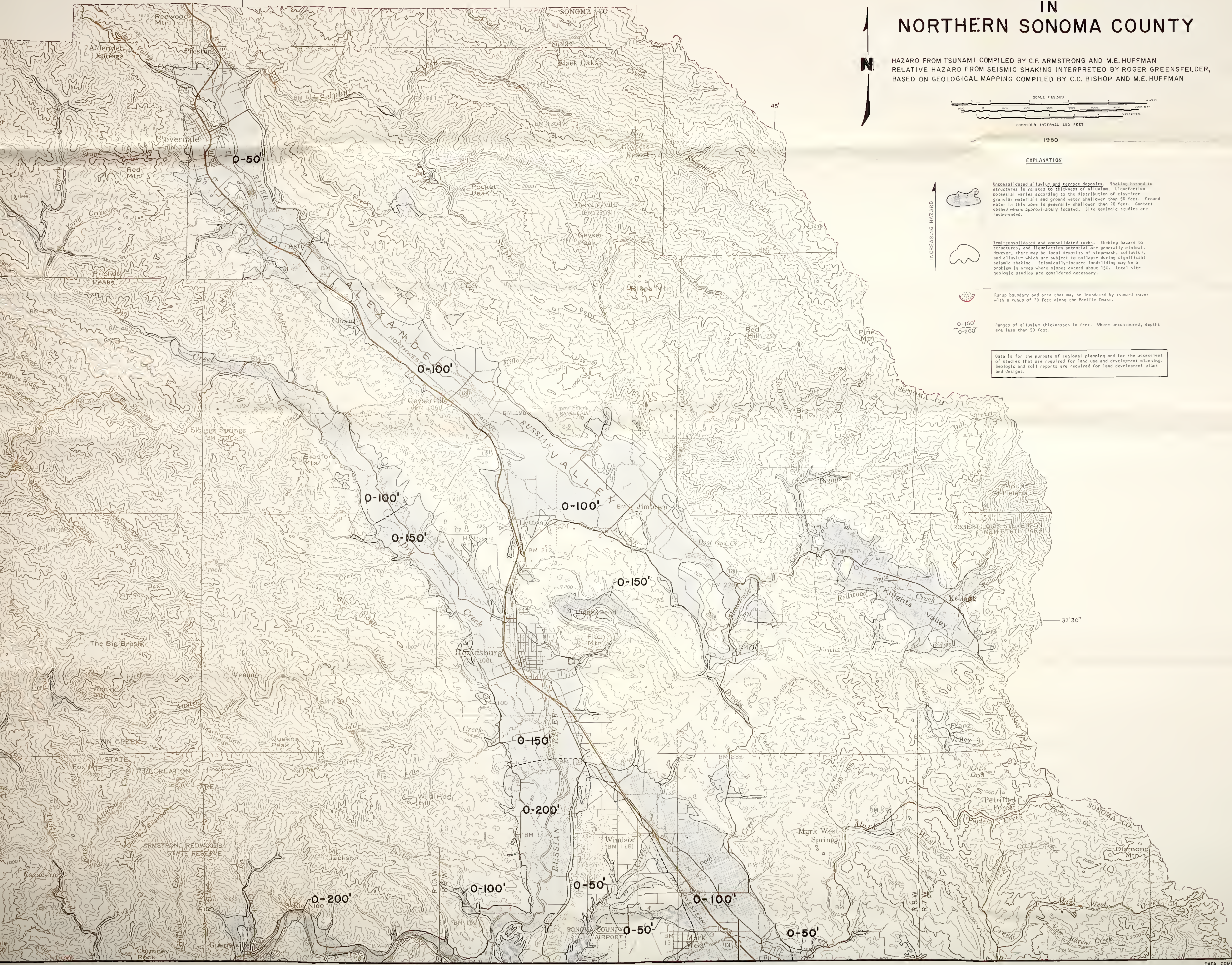
RELATIVE HAZARD FROM TSUNAMI AND SEISMIC SHAKING IN NORTHERN SONOMA COUNTY

HAZARO FROM TSUNAMI COMPILED BY C.F. ARMSTRONG AND M.E. HUFFMAN
RELATIVE HAZARD FROM SEISMIC SHAKING INTERPRETED BY ROGER GREENSFELDER,
BASED ON GEOLOGICAL MAPPING COMPILED BY C.C. BISHOP AND M.E. HUFFMAN

SCALE 1:62,500

COUNTOUR INTERVAL 200 FEET

1980



EXPLANATION

INCREASING HAZARD

▨	Unconsolidated alluvium and terrace deposits. Shaking hazard to structures is related to thickness of alluvium. Liquefaction potential varies according to the distribution of clay-free granular materials and ground water shallower than 50 feet. Ground water in this zone is generally shallower than 20 feet. Contact dashed where approximately located. Site geologic studies are recommended.
☐	Semi-consolidated and consolidated rocks. Shaking hazard to structures, and liquefaction potential are generally minimal. However, there may be local deposits of slopewash, colluvium, and alluvium which are subject to collapse during significant seismic shaking. Seismically-induced landsliding may be a problem in areas where slopes exceed about 15%. Local site geologic studies are considered necessary.
◡	Runup boundary and area that may be inundated by tsunami waves with a runup of 20 feet along the Pacific Coast.
0-150' 0-200'	Ranges of alluvium thicknesses in feet. Where uncontoured, depths are less than 50 feet.

Data is for the purpose of regional planning and for the assessment of studies that are required for land use and development planning. Geologic and soil reports are required for land development plans and designs.

DATA COMPILED 1973-74

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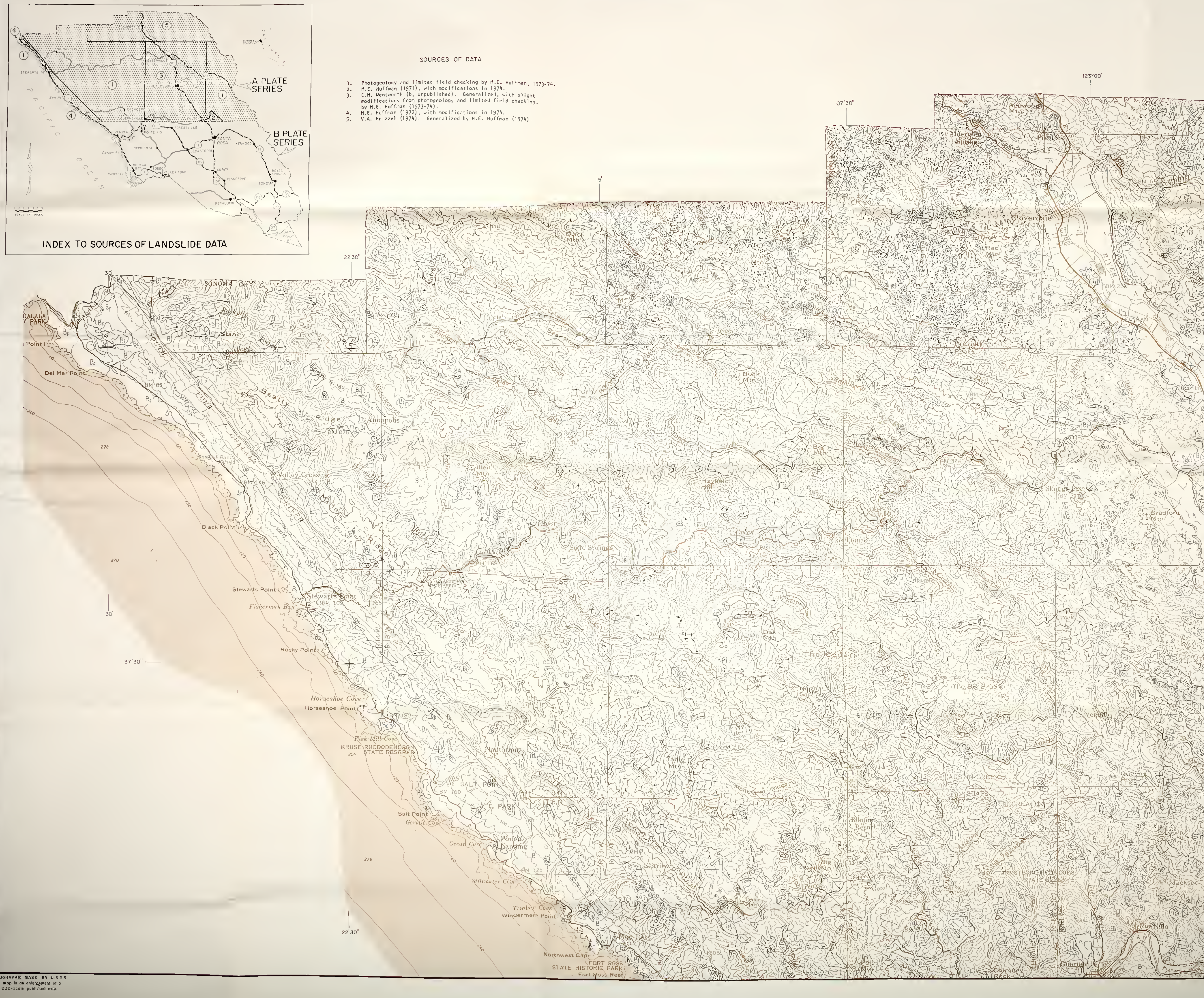

INDEX TO SOURCES OF LANDSLIDE DATA

SOURCES OF DATA

1. Photogeology and limited field checking by M.E. Huffman, 1973-74.
2. M.E. Huffman (1971), with modifications in 1974.
3. C.M. Wentworth (b, unpublished). Generalized, with slight modifications from photogeology and limited field checking, by M.E. Huffman (1973-74).
4. M.E. Huffman (1972), with modifications in 1974.
5. V.A. Frizzel (1974). Generalized by M.E. Huffman (1974).

TOPOGRAPHIC BASE BY U.S.G.S
This map is an enlargement of a 1:125,000-scale published map.

C3
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PREPARED BY THE CALIFORNIA DIVISION OF MINES AND GEOLOGY
IN COOPERATION WITH THE SONOMA COUNTY PLANNING DEPARTMENT

SLOPE STABILITY
SPECIAL REPORT 120 PLATE 2A

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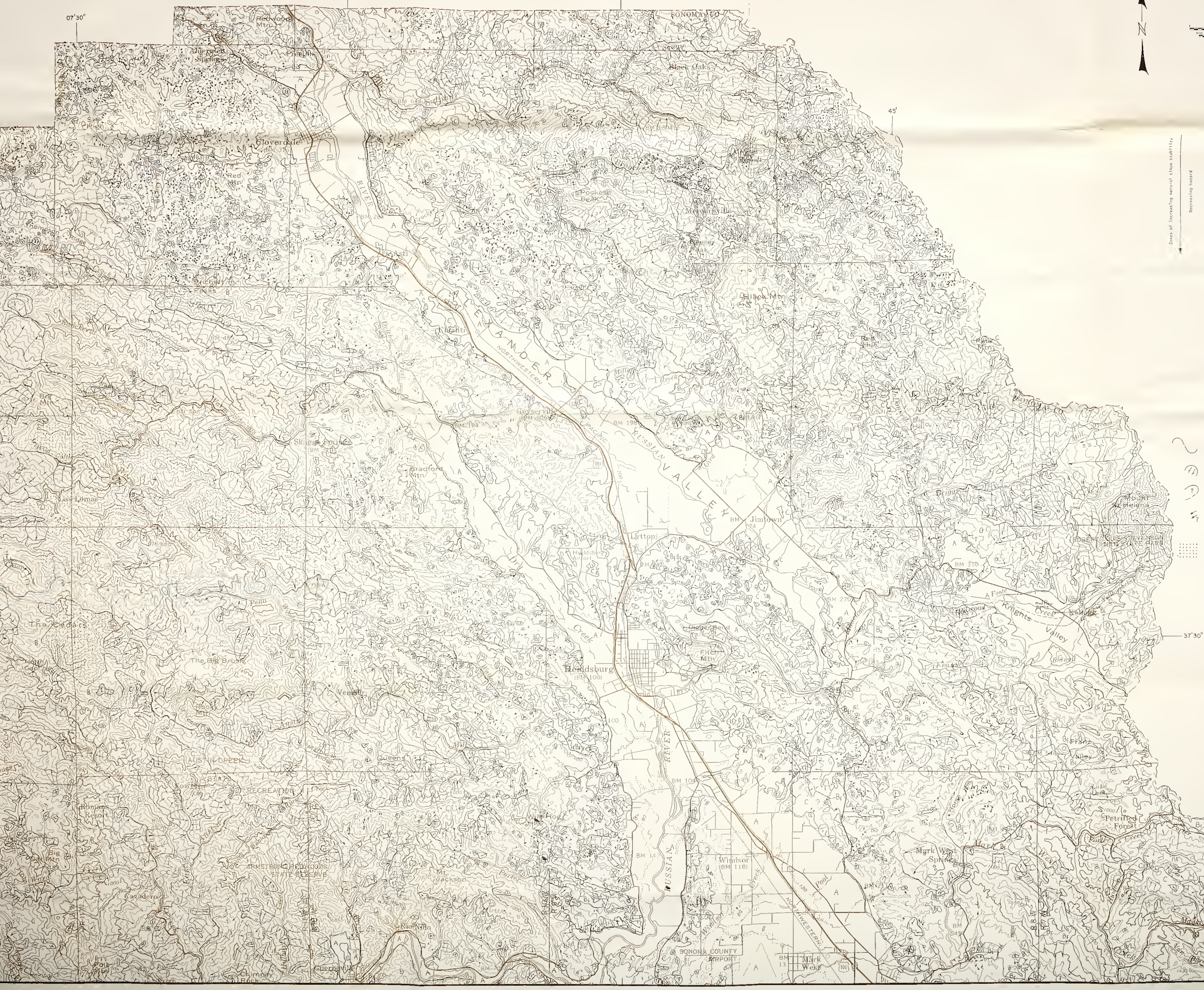
LANDSLIDES AND RELATIVE SLOPE STABILITY - NORTHERN SONOMA COUNTY

by

Michael E. Huffman



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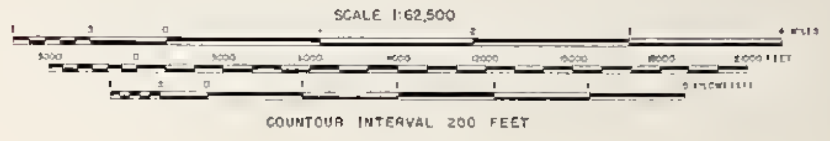

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EXPLANATION

Relative Slope Stability Categories

Zones of increasing natural slope stability

Decreasing hazard

Landslides

Areas of lowest relative slope stability. Failure and downslope movement of rock and soil has occurred, or may have occurred ("possible" landslides).

C

Areas of relatively unstable rock and soil units, on slopes greater than 15%, containing abundant landslides.

B

Areas of relatively stable rock and soil units, on slopes greater than 15%, containing few landslides.

B_f

Locally level areas within hilly terrain; may be underlain or bounded by unstable or potentially unstable rock materials.

A

Areas of greatest relative stability due to low slope inclination - dominantly less than 15%.

Note: Geologic conditions in areas labeled B_f, B, C, and landslides mandate that engineering geology reports must be required prior to tentative tract approval for land use planning and land development.

Note: Categories are interpretive and apply generally to large areas. Within each area conditions may range in detail through all four stability categories. Hence, an A area may locally contain unmapped landslides, and a landslide area may contain stable slopes of slight inclination.

Landslide Symbols

Contact between landslide deposits; landslides and more stable ground; or areas of differing slope stability. Dashed line indicates an approximate location.

General direction of landslide movement.

? Query indicates possible landslide.

? Landslide or severe soil creep area too small to be outlined at the map scale. Question mark adjacent to arrow indicates landslide is uncertain, or "possible".

Zones of numerous small landslides. Used in the more remote northern portions of the County where the limitations of time and scope of this study did not allow detailed plotting. These zones include rockfall and talus slopes on Mt. Saint Helena and The Cedars, and areas of severe surficial slippage and gully-bank slumping. Site geologic studies are considered mandatory.

Data is for the purpose of regional planning and for the assessment of studies that are required for land use and development planning. Geologic and soil reports are required for land development plans and designs.

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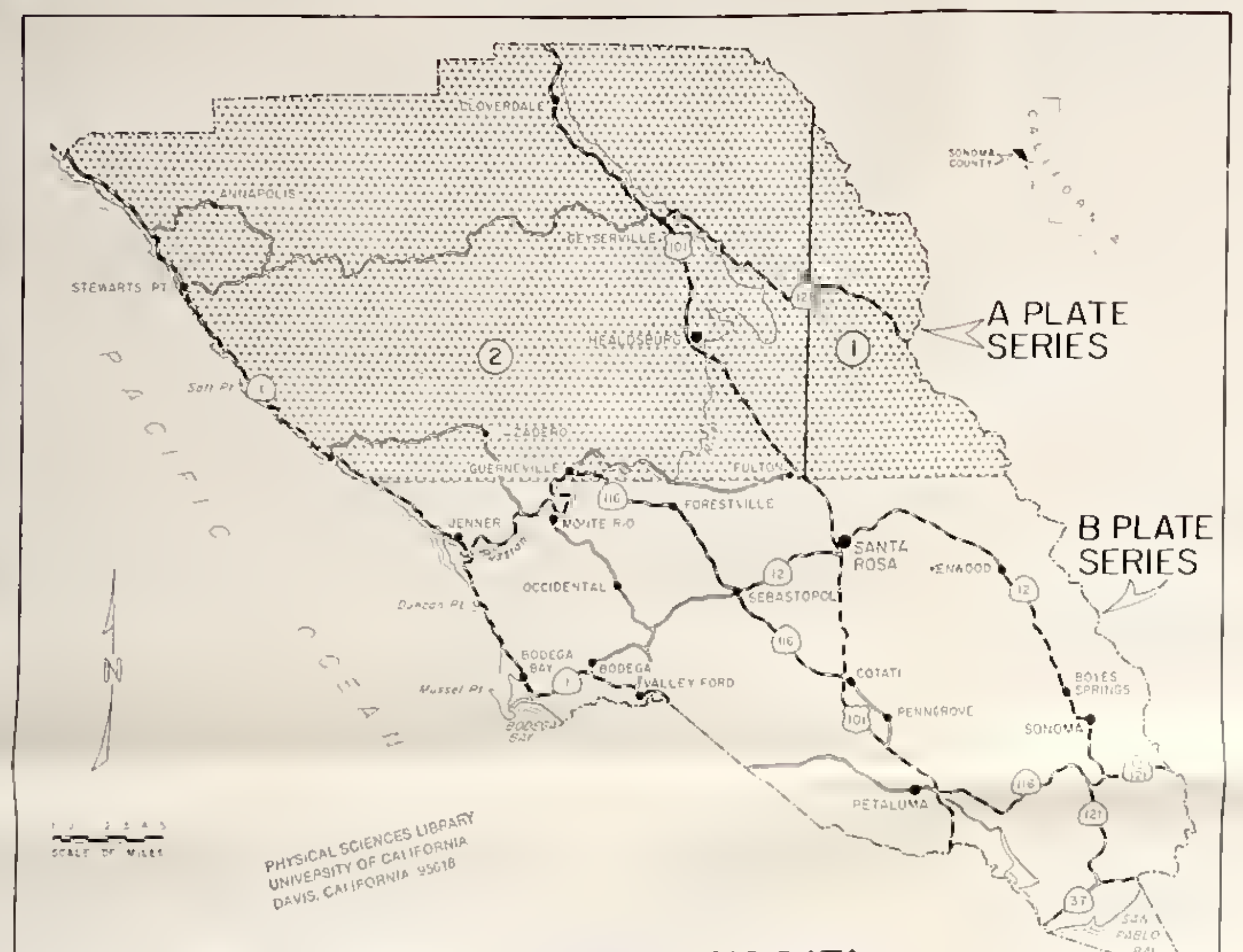

INDEX TO SOURCES OF GEOLOGIC DATA

SOURCES OF DATA

*1. Fox, K.F. Jr., et al (1973) with slight modifications by M.E. Huffman (1974).
*2. Blake, M.C. Jr., (1971) with slight modifications by M.E. Huffman (this study). Some coastal terrace deposits and faults are from Huffman (1972).

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*U.S. Geological Survey, Basic Data Contributions.

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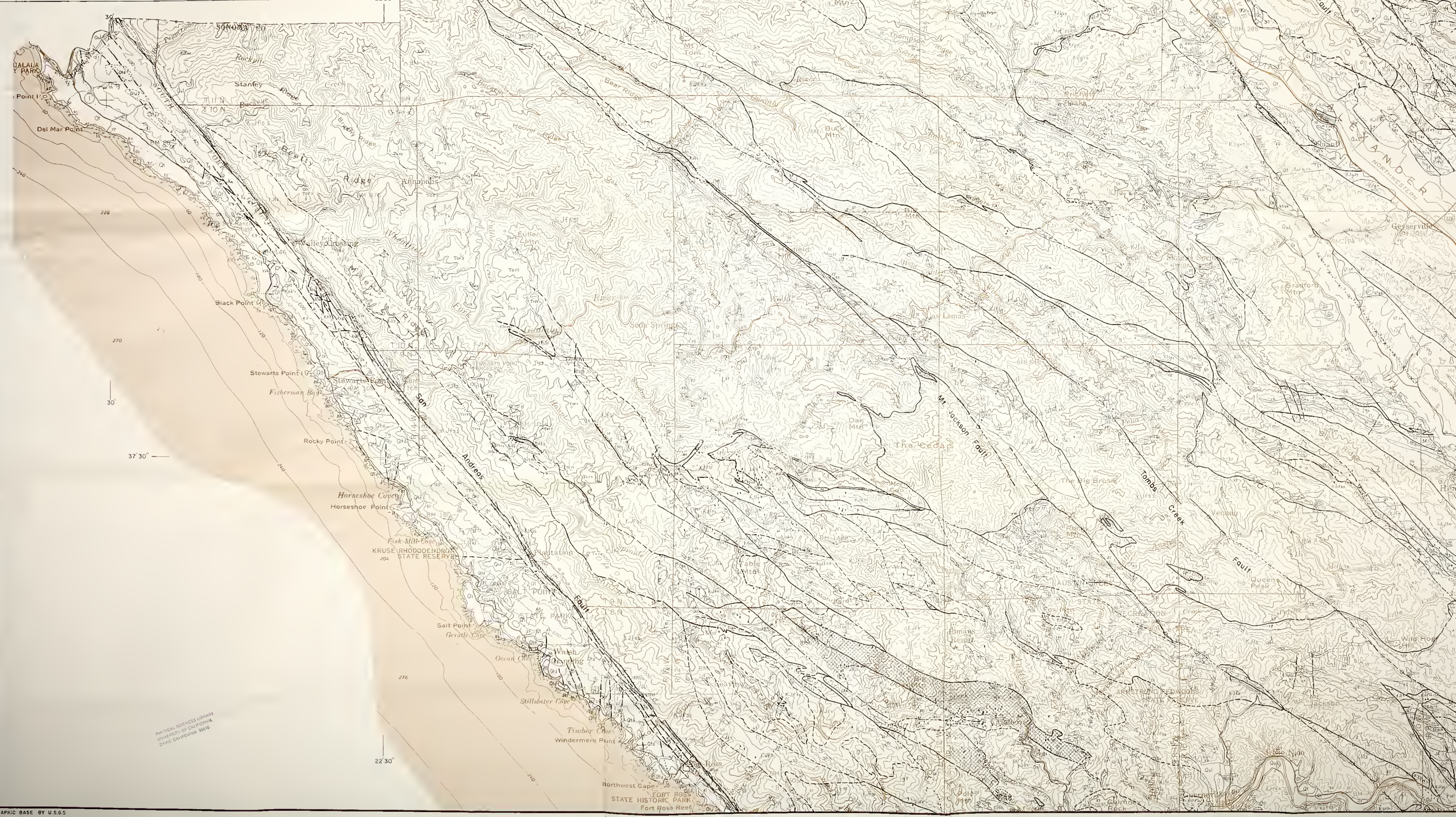

TOPOGRAPHIC BASE BY U.S.G.S
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TN 24
C3
A33
no 120
plate 3A

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IN COOPERATION WITH THE SONOMA COUNTY PLANNING DEPARTMENT

GEOLOGIC MAP EXCLUSIVE OF LANDSLIDES - NORTHERN SONOMA COUNTY

compiled by

Richard D. Knox and Michael E. Huffman

SCALE 1:62,500

COUNTOUR INTERVAL 200 FEET

1980

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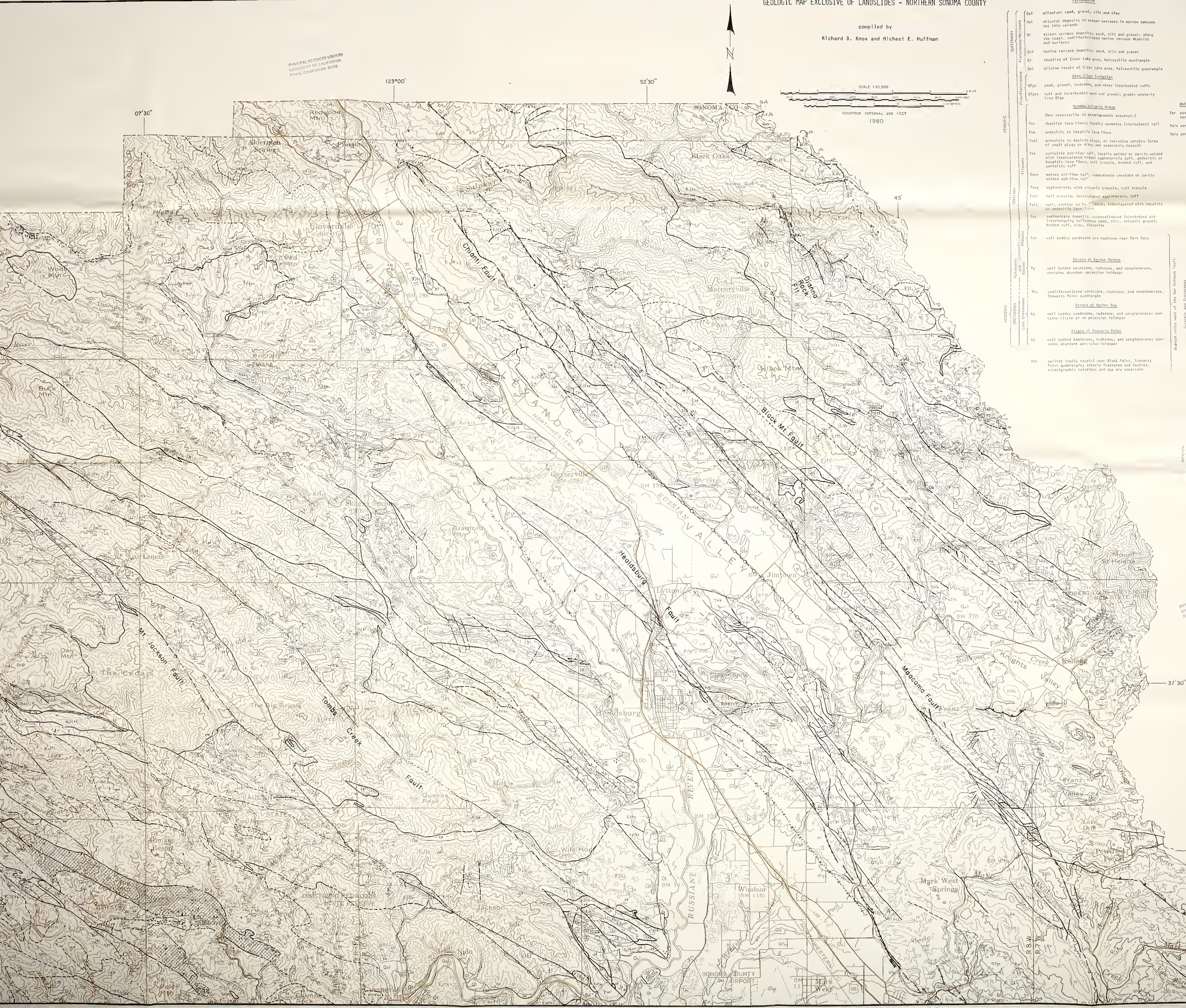

EXPLANATION

CENOZOIC

QUATERNARY

Pleistocene-Holocene

Qal	alluvium: sand, gravel, silt and clay
Qol	alluvial deposits on stream terraces in narrow canyons cut into uplands
Qt	stream terrace deposits; sand, silt and gravel; along the coast, undifferentiated marine terrace deposits and surfaces
Qtd	marine terrace deposits; sand, silt and gravel
Qr	rhyolite of Clear Lake area, Kelseyville quadrangle
Qob	olivine basalt of Clear Lake area, Kelseyville quadrangle

Plio-Pleistocene

Glen Ellen Formation

QTge	sand, gravel, mudstone, and minor interbedded tuffs
QTget	tuff and interbedded sand and gravel; grades westerly into QTge

TERTIARY

Pliocene

Sonoma Volcanic Group

(Not necessarily in stratigraphic sequence.)

Tsr	rhyolite lava flows; locally contains intercalated tuff
Tsa	andesitic to basaltic lava flows
Tsai	andesitic to dacitic plugs, or intrusive complex (area of small plugs or dikes not separately mapped)
Tst	pumicitic ash-flow tuff, locally welded or partly welded with intercalated bedded agglomeritic tuff, andesitic or basaltic lava flows, tuff breccia, bedded tuff, and pumicitic tuff
Tswt	welded ash-flow tuff, subordinate unwelded or partly welded ash-flow tuff
Tsag	agglomerate; with volcanic breccia, tuff breccia
Tslt	tuff breccia; intercalated agglomerate, tuff
Tslt	tuff, similar to Tst, thinly interlayered with basaltic or andesitic lava flows
Tss	sedimentary deposits; unconsolidated interbedded and intertonguing tuffaceous sand, silt, volcanic gravel; bedded tuff, clay, diatomite

Ohlson Ranch Formation

Tor	sandstone, siltstone, conglomerate
Tors	sandstone
Torc	conglomerate

"Merced" Formation

Tm	fine-grained sandstone and local minor coarse-grained grit and tuff breccia, poorly indurated

Petaluma (?) Formation

Tp	undivided claystone, siltstone, mudstone, tuff with sandstone and conglomerate coarse beds

Bedrock units west of the San Andreas fault

Miocene

Tsm	well bedded sandstone and mudstone near Fort Ross

Paleocene and Eocene

Strata of German Rancho

Tg	well bedded sandstone, mudstone, and conglomerate, contains abundant potassium feldspar
TKu	undifferentiated sandstone, mudstone, and conglomerate, Stewarts Point quadrangle

MESOZOIC

CRETACEOUS

Late Cretaceous

Strata of Anchor Bay

Ka	well bedded sandstone, mudstone, and conglomerate; contains little or no potassium feldspar

Strata of Stewarts Point

Ks	well bedded sandstone, mudstone, and conglomerate; contains abundant potassium feldspar
Ksb	spilite (sodic basalt) near Black Point, Stewarts Point quadrangle; closely fractured and faulted, stratigraphic relations and age are uncertain

Jurassic and Cretaceous

Great Valley Sequence

KJgv	undifferentiated rock; mainly well bedded sandstone, shale and conglomerate
KJgvs	siltstone with minor sandstone
KJgvc	conglomerate

Jurassic

Igneous rocks locally present at base of Great Valley Sequence

Jv	basaltic pillow lava and breccia
Jd	diabase, gabbro, quartz diabase, quartz gabbro, and trondhjemite
Ju	ultramafic rock, largely pyroxenite, includes serpentine

Jurassic and Cretaceous

Franciscan Assemblage

(Not necessarily in correct time sequence.)

KJlss	predominantly graywacke-type sandstone and shale with minor greenstone, conglomerate, chert, and limestone. Rock pervasively shattered and commonly veined with laumontite. Sandstone massive and well bedded to locally thin-bedded and flysch-like, and contains about 5 to 25 percent detrital potassium feldspar
KJfm	chiefly metagraywacke with slight to pronounced metamorphic fabric and minor metagreenstone and metachert; contains blueschist minerals, including glaucophane, lawsonite, and jadeitic pyroxene. Metagraywacke contains no detrital potassium feldspar
KJfs	sheared shale and sandstone that contains generally resistant masses of chert, "high grade" metamorphic rock, variable shattered sandstone and greenstone, metagreenstone, and generally less resistant serpentinite (see table below for lithologies and map symbols); masses range in length from less than one foot to greater than 5 miles, and constitute a variable, generally unknown proportion of the unit. Potassium feldspar generally absent. Parts of unit correspond to melange unit described by Hsu (1969).

Rock types that occur as discrete masses, chiefly within KJfs

sp	serpentinite, including relatively fresh ultramafic masses. Occurs as lenses, sheets, and irregularly shaped masses, largely within and along boundaries of KJls
sc	silica-carbonate rock
ch	chert, including metachert
gs	greenstone, including pillow lava, tuff, minor intrusive varieties, and minor fossiliferous limestone, and metagreenstone ranging from rock containing incipient blueschist minerals to completely reconstituted blueschist. Masses range to longer than 5 miles.
▨	Foliate metabasalt in the southern Skaggs Springs quadrangle
	graywacke-type sandstone, containing 0 to 5 percent detrital potassium feldspar, and some metagraywacke. Probably occurs in masses ranging to at least several miles long; map distribution largely unknown
m, ◆	"high grade" metamorphic rock, chiefly gneissic, including glaucophane schist, eclogite, and amphibolite, most occurring in blocks less than 100 feet long
mi	mafic intrusive rocks, chiefly fine- to coarse-grained gabbro and diorite

SYMBOLS

Contact; solid line where well located, long dash where approximately located, short dash where inferred (gradational in the Calistoga 15 minute quadrangle), dotted where concealed; query indicates additional uncertainty.

Fault; solid line where well located, long dash where approximately located, short dash where inferred, dotted where concealed; query indicates additional uncertainty. Arrow and number indicate direction and amount of dip in degrees. Whether or not the fault is active or poses any hazard to man is generally unknown. Only crosscutting faults are shown within KJfs, although most contacts therein probably are faults.

Potentially active fault. These faults exhibit features indicative of geologically young (Quaternary) surface rupture. Therefore, they are considered to be capable of renewed surface movement.

Possibly active fault. These faults exhibit features suggestive (but not conclusive) of geologically young (Quaternary) surface rupture. Further studies are necessary to determine their potential activity.

Thrust fault; dashed where approximately located, queried where doubtful. Sawteeth on upper plate.

Syncline; dashed where approximately located.

Dip and strike of bedding:

10	inclined
⊕	horizontal
+	vertical
70	overturned
40	Dip and strike of flow banding

Data is for the purpose of regional planning and for the assessment of studies that are required for land use and development planning. Geologic and soil reports are required for land development plans and designs.

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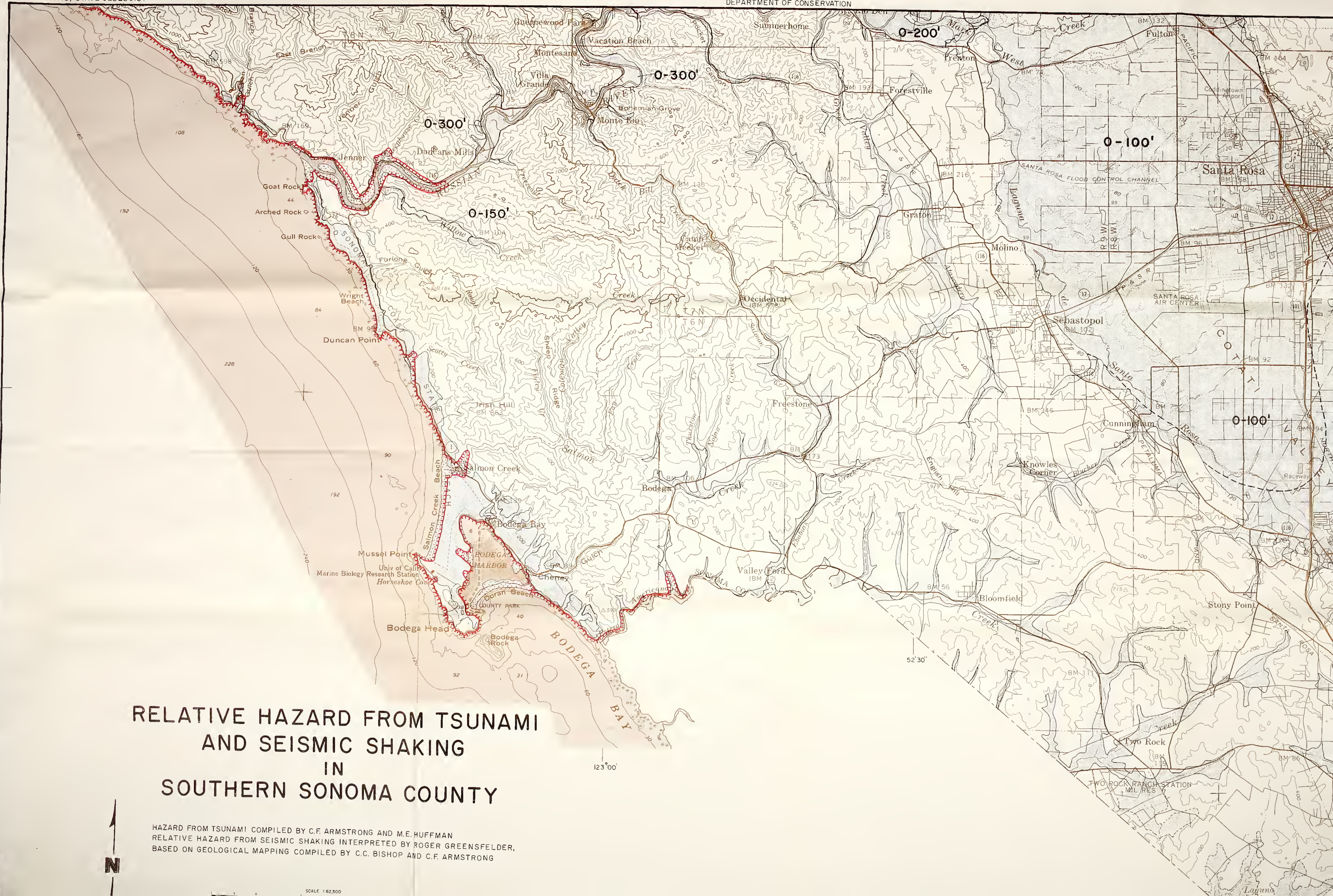

RELATIVE HAZARD FROM TSUNAMI AND SEISMIC SHAKING IN SOUTHERN SONOMA COUNTY

HAZARD FROM TSUNAMI COMPILED BY C.F. ARMSTRONG AND M.E. HUFFMAN
RELATIVE HAZARD FROM SEISMIC SHAKING INTERPRETED BY ROGER GREENSFELDER,
BASED ON GEOLOGICAL MAPPING COMPILED BY C.C. BISHOP AND C.F. ARMSTRONG

N

SCALE 1:62,500

PREPARED BY THE CALIFORNIA DIVISION OF MINES AND GEOLOGY
IN COOPERATION WITH THE SONOMA COUNTY PLANNING DEPARTMENT

SEISMIC SHAKING
SPECIAL REPORT 120 PLATE 1B

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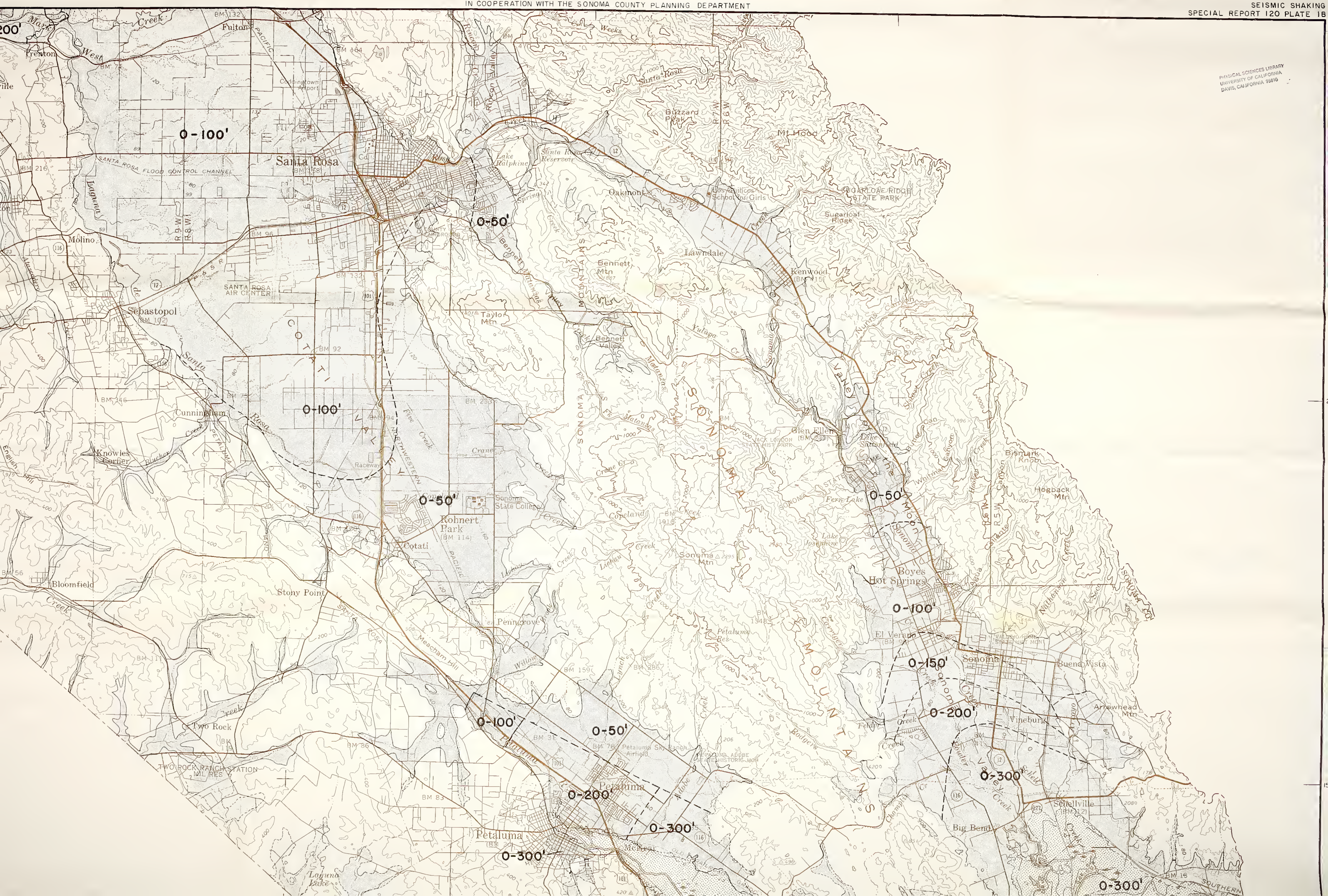

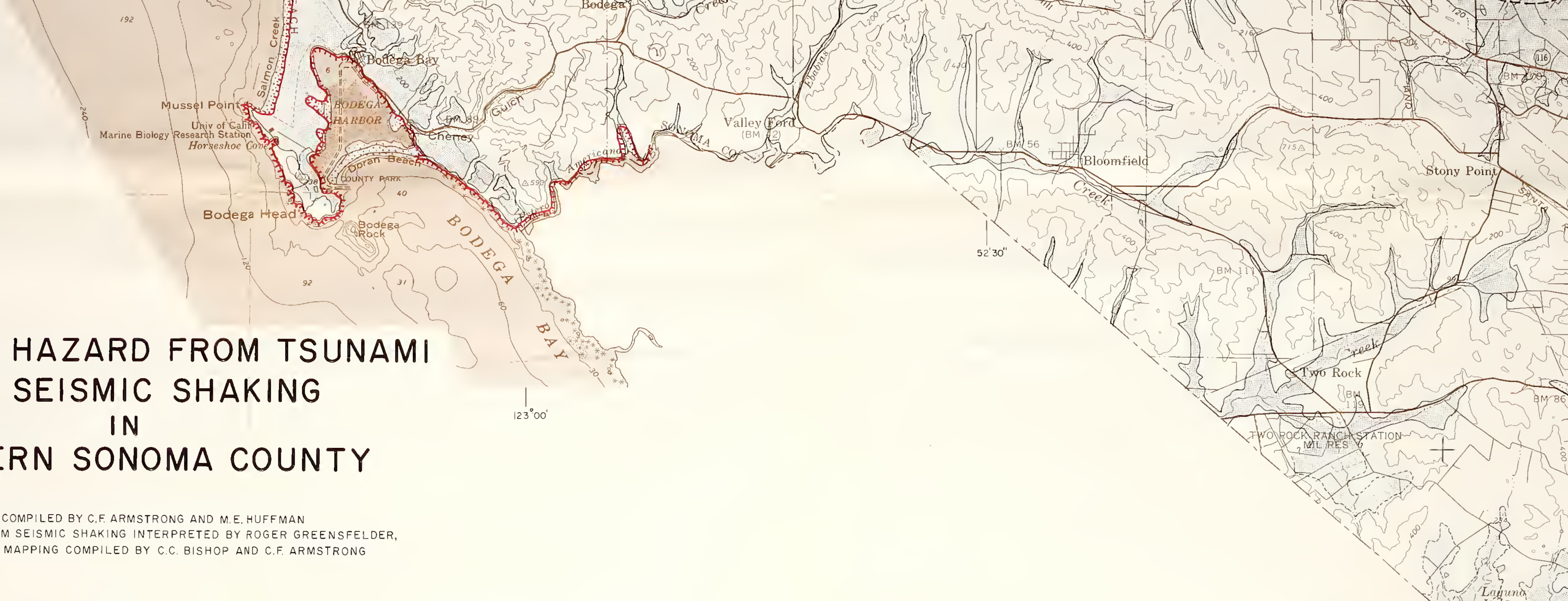

RELATIVE HAZARD FROM TSUNAMI AND SEISMIC SHAKING IN SOUTHERN SONOMA COUNTY

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BASED ON GEOLOGICAL MAPPING COMPILED BY C.C. BISHOP AND C.F. ARMSTRONG

SCALE 1:62,500

COUNTOUR INTERVAL 200 FEET

1980

EXPLANATION

INCREASING HAZARD

▒	Younger bay mud. This is among the most unstable deposits in the County, and liquefaction should be expected where clay-free granular materials (e.g. clean sand deposits) are present. Site geologic studies are recommended.
░	Unconsolidated alluvium and terrace deposits. Shaking hazard to structures is related to thickness of alluvium. Liquefaction potential varies according to the distribution of clay-free granular materials and ground water shallower than 50 feet. Ground water in this zone is generally shallower than 20 feet. Contact dashed where approximately located. Site geologic studies are recommended.
○	Semi-consolidated and consolidated rocks. Shaking hazard to structures, and liquefaction potential are generally minimal. However, there may be local deposits of slopewash, colluvium, and alluvium which are subject to collapse during significant seismic shaking. Seismically-induced landsliding may be a problem in areas where slopes exceed about 15%. Local site geologic studies are recommended.
◠	Runup boundary and area that may be inundated by tsunami waves with a runup of 20 feet along the Pacific Coast. (Boundaries from Ritter and Dupre, 1972: U.S. Geological Survey Basic Data Contribution 52.)
0-150' / 0-200'	Ranges of alluvium thicknesses in feet. Where uncontoured, depths are less than 50 feet.
— — 40' — —	Thickness of Younger bay mud in feet.

Data is for the purpose of regional planning and for the assessment of studies that are required for land use and development planning. Geologic and soil reports are required for land development plans and designs.

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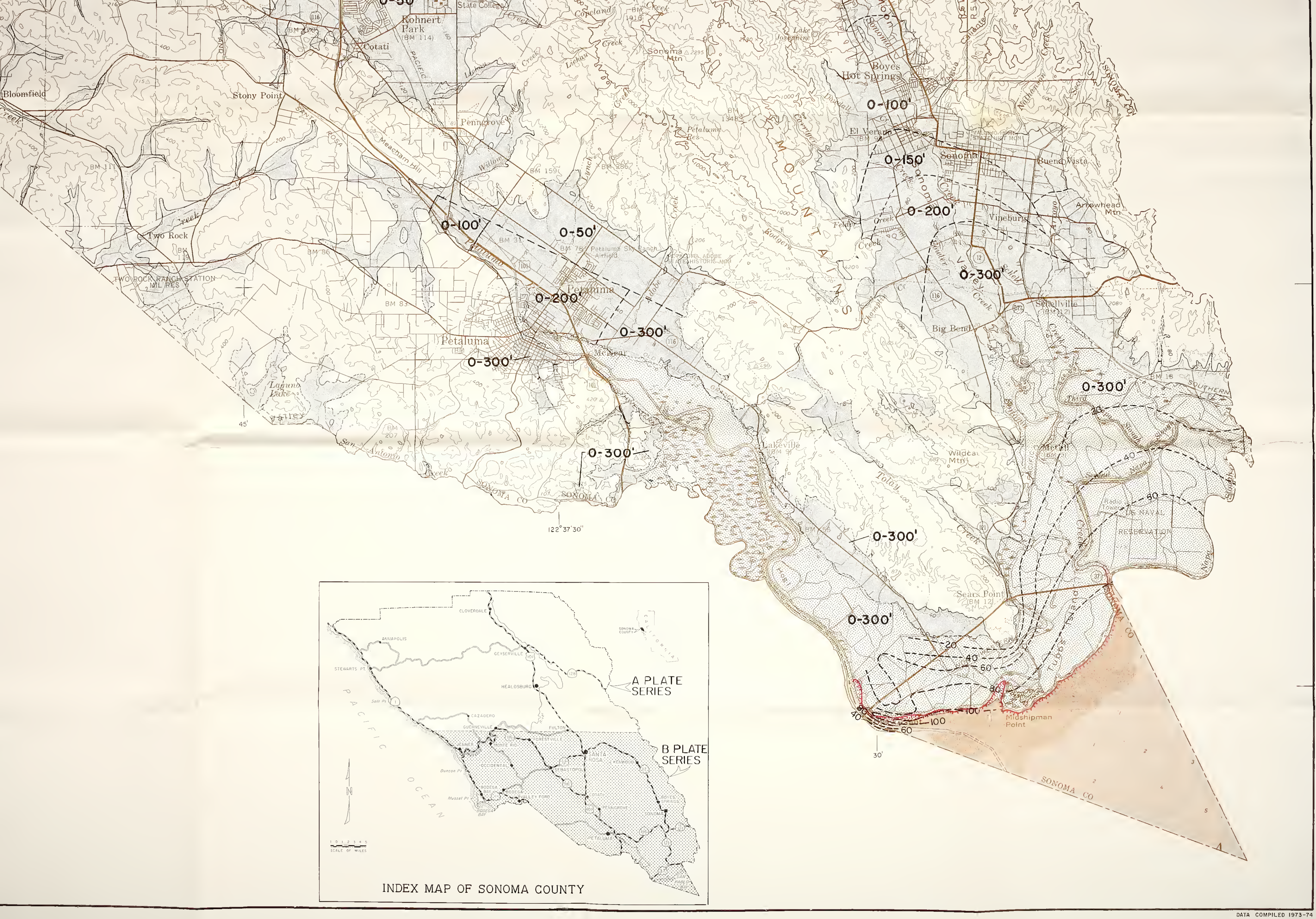

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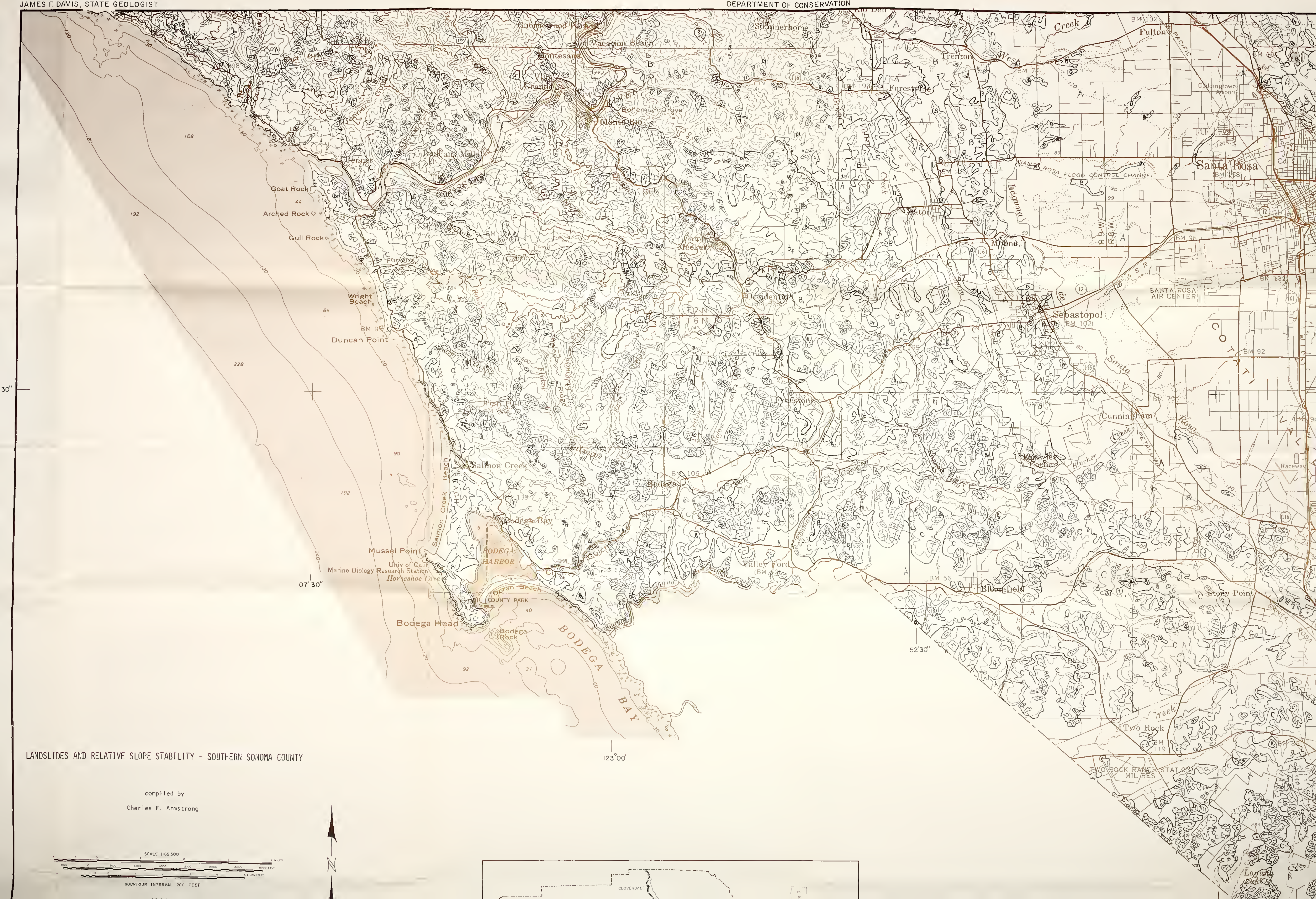

LANDSLIDES AND RELATIVE SLOPE STABILITY - SOUTHERN SONOMA COUNTY

compiled by

Charles F. Armstrong

SCALE 1:62,500

COUNTOUR INTERVAL 200 FEET

PREPARED BY THE CALIFORNIA DIVISION OF MINES AND GEOLOGY
IN COOPERATION WITH THE SONOMA COUNTY PLANNING DEPARTMENT

SLOPE STABILITY
SPECIAL REPORT 120 PLATE 2B

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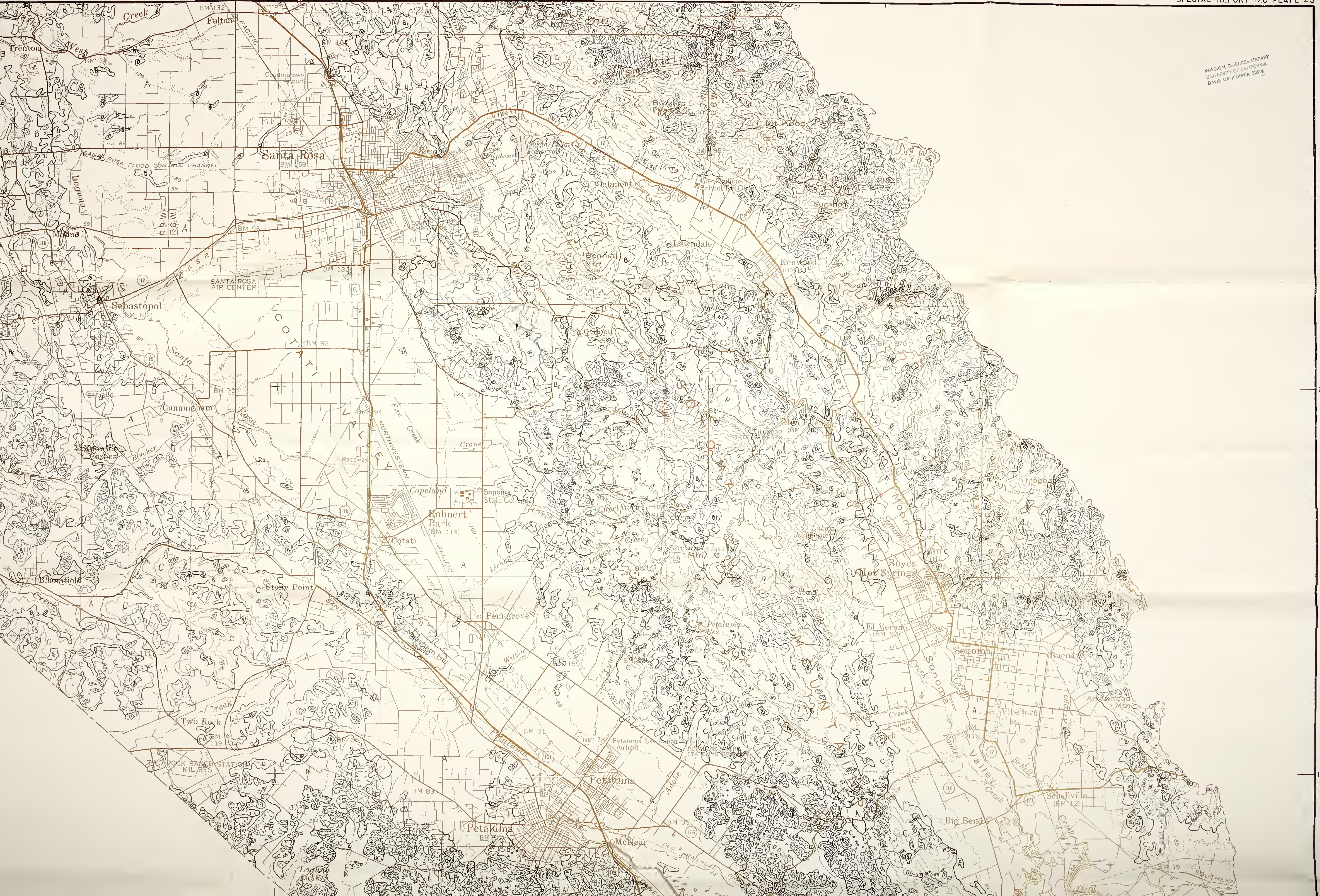

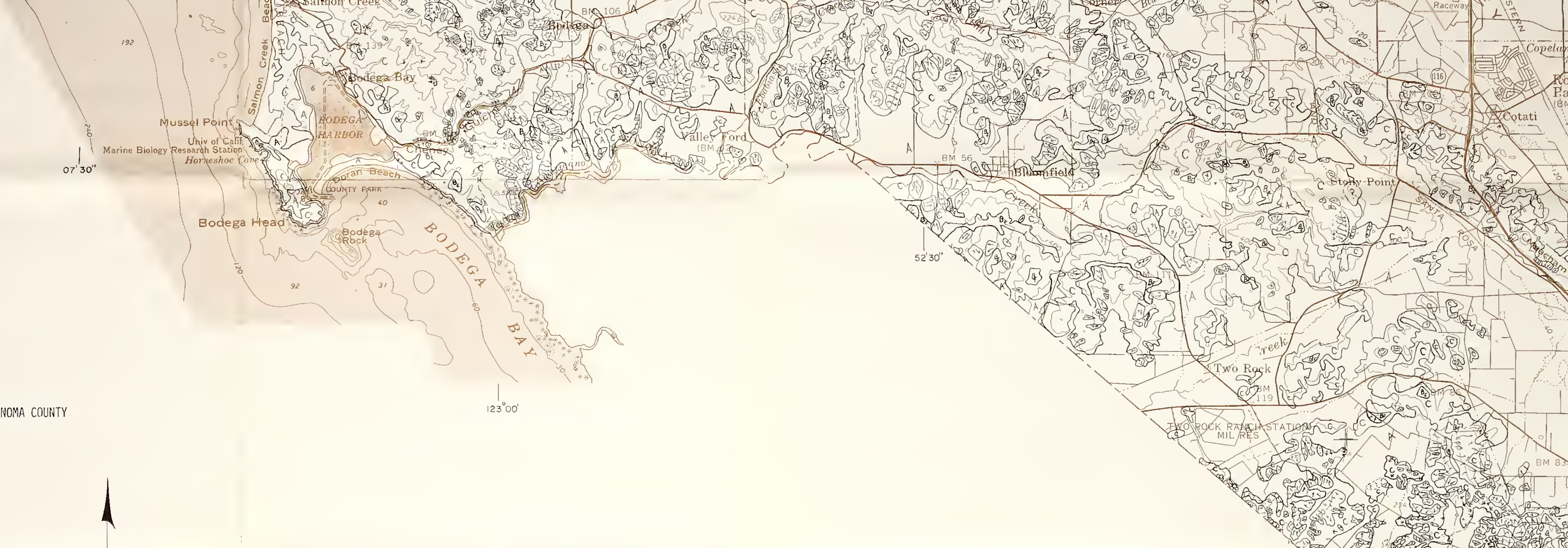

LANDSLIDES AND RELATIVE SLOPE STABILITY - SOUTHERN SONOMA COUNTY

compiled by

Charles F. Armstrong

SCALE 1:62,500

COUNTOUR INTERVAL 200 FEET

1980

EXPLANATION

Relative Slope Stability Categories

Zones of increasing natural slope stability — Decreasing hazard

Landslides

(see "Landslide Symbols" below)

Areas of lowest relative slope stability. Failure and downslope movement of rock and soil have occurred, or may have occurred ("possible" landslides).

C

Areas of relatively unstable rock and soil units, on slopes greater than 15%, containing abundant landslides.

B

Areas of relatively stable rock and soil units, on slopes greater than 15%, containing few landslides.

B_f

Locally level areas within hilly terrain; may be underlain or bounded by unstable or potentially unstable rock materials.

A

Areas of greatest relative stability due to low slope inclination - dominantly less than 15%.

Note: Geologic conditions in areas labeled B_f, B, C, and landslides mandate that engineering geology reports must be required prior to tentative tract approval for land use planning and land development within those areas.

Note: Categories are interpretive and apply generally to large areas. Within each area conditions may range in detail through all four stability categories. Hence, an A area may locally contain unmapped landslides, and a landslide area may contain stable slopes of slight inclination.

Contact Symbols

Contact between landslide deposits; landslides and more stable ground; or areas of differing slope stability. Dashed line indicates an approximate location.

Landslide Symbols

Landslide: arrows with one barb show general direction of movement.

Possible landslide.

Indicates a generalized area of landslides and unstable soil, undifferentiated in details of size or direction of movement.

↙ Landslide or severe soil creep area too small to be outlined at the map scale.

Data is for the purpose of regional planning and for the assessment of studies that are required for land use and development planning. Geologic and soil reports are required for land development plans and designs.

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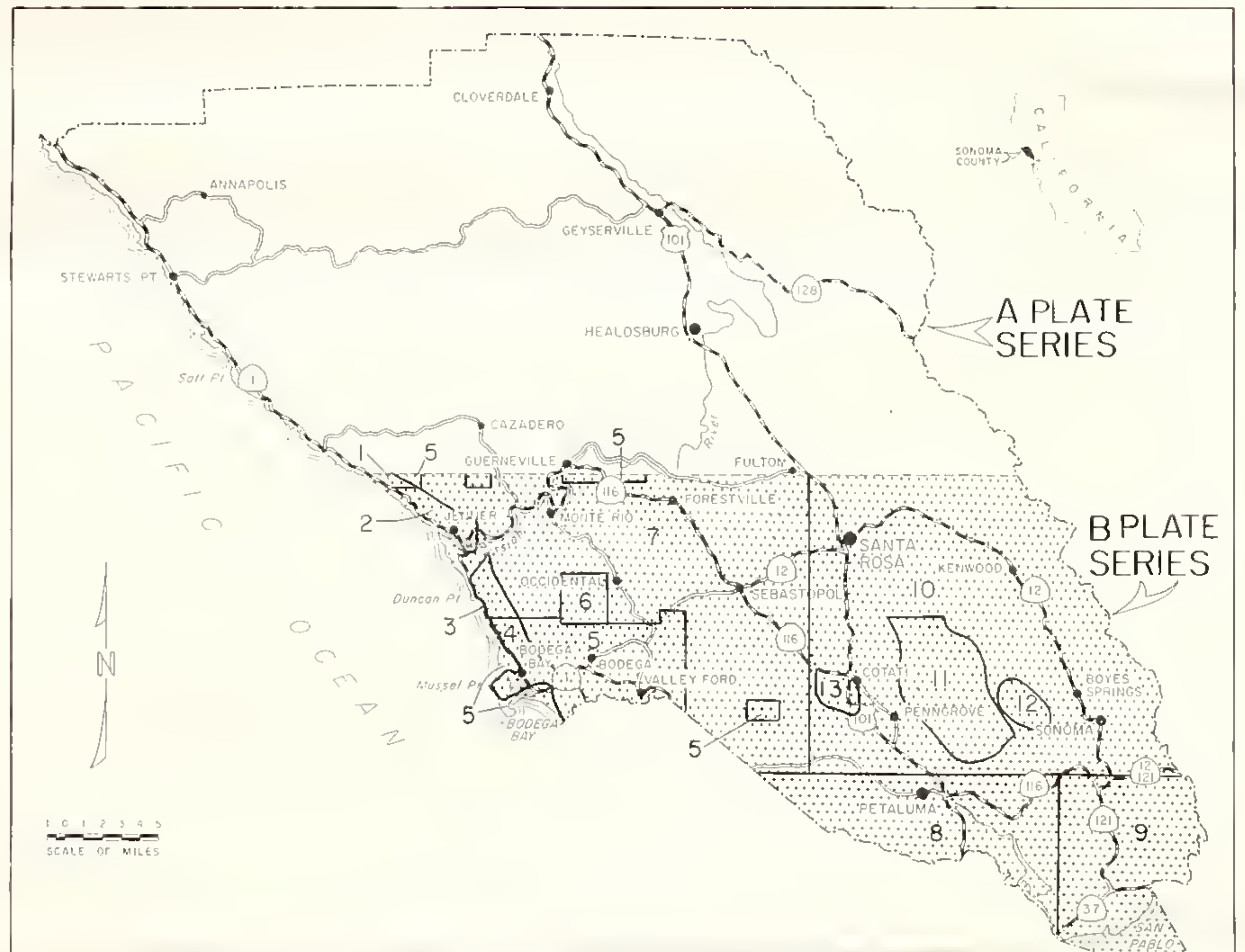

INDEX TO SOURCES OF LANDSLIDE DATA

1. Huffman, M.E., 1972, modified by Armstrong, C.F., 1974.
2. Huffman, M.E., 1972, and Morton, D.M., unpublished.
3. Huffman, M.E., 1973, and Morton, D.M., unpublished.
4. Huffman, M.E., 1973, modified by Armstrong, C.F., 1974.
5. Armstrong, C.F., aerial photo interpretation, 1974.
6. Morton, D.M., unpublished, modified by Armstrong, C.F., 1974.
7. Morton, D.M., unpublished, modified by Armstrong, C.F., 1974.
8. Wentworth, C.W. (a), unpublished, modified by Armstrong, C.F., 1974.
9. Armstrong, C.F., aerial photo interpretation, 1974, and Sims, J.D., et al, 1973.
10. Armstrong, C.F., aerial photo interpretation, 1974, and Fox, K.F. Jr., et al, 1973.
11. Huffman, M.E., 1971, and Fox, K.F. Jr., et al, 1973, modified by Armstrong, C.F., 1974.
12. Owyer, M.J., 1974.
13. Frenaye, T., unpublished, modified by Armstrong, C.F., 1974.

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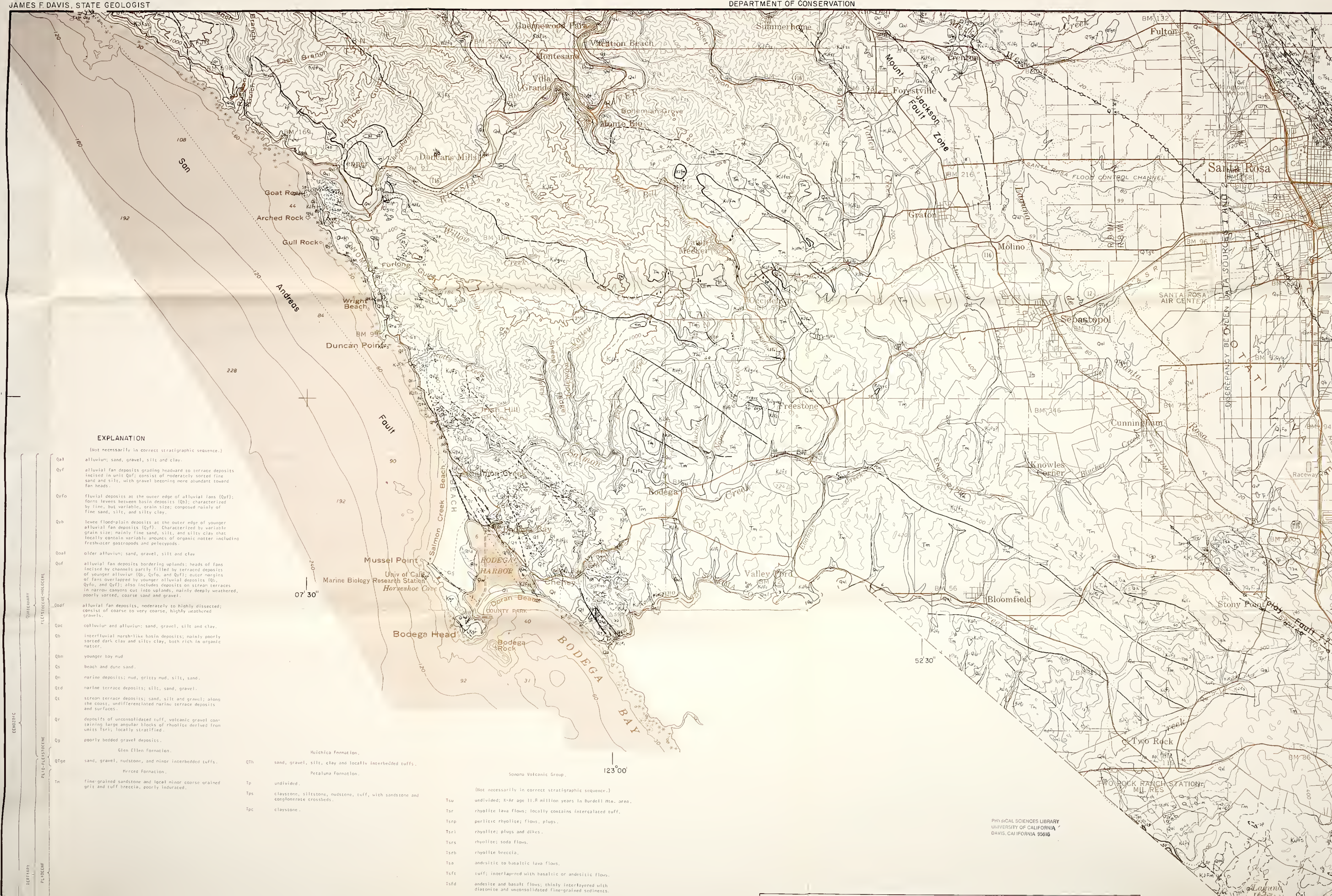

EXPLANATION

(Not necessarily in correct stratigraphic sequence.)

CENOZOIC
QUATERNARY
PLEISTOCENE-HOLOCENE
PLIO-PLEISTOCENE
TERTIARY
PLIOCENE

Qal	alluvium; sand, gravel, silt and clay.
Qyf	alluvial fan deposits grading headward to terrace deposits incised in unit Qof; consist of moderately sorted fine sand and silt, with gravel becoming more abundant toward fan heads.
Qyfo	fluvial deposits at the outer edge of alluvial fans (Qyf); forms levees between basin deposits (Qb); characterized by fine, but variable, grain size; composed mainly of fine sand, silt, and silty clay.
Qyb	levee flood-plain deposits at the outer edge of younger alluvial fan deposits (Qyf). Characterized by variable grain size: mainly fine sand, silt, and silty clay that locally contain variable amounts of organic matter including freshwater gastropods and pelecypods.
Qoal	older alluvium; sand, gravel, silt and clay
Qof	alluvial fan deposits bordering uplands: heads of fans incised by channels partly filled by terraced deposits of younger alluvium (Qb, Qyfo, and Qyf); outer margins of fans overlapped by younger alluvial deposits (Qb, Qyfo, and Qyf); also includes deposits on stream terraces in narrow canyons cut into uplands, mainly deeply weathered, poorly sorted, coarse sand and gravel.
Qodf	alluvial fan deposits, moderately to highly dissected; consist of coarse to very coarse, highly weathered gravels.
Qac	colluvium and alluvium: sand, gravel, silt and clay.
Qb	interfluvial marsh-like basin deposits; mainly poorly sorted dark clay and silty clay, both rich in organic matter.
Qbm	younger bay mud
Qs	beach and dune sand.
Qm	marine deposits; mud, gritty mud, silt, sand.
Qtd	marine terrace deposits; silt, sand, gravel.
Qt	stream terrace deposits; sand, silt and gravel; along the coast, undifferentiated marine terrace deposits and surfaces.
Qr	deposits of unconsolidated tuff, volcanic gravel containing large angular blocks of rhyolite derived from units Tsri; locally stratified.
Qg	poorly bedded gravel deposits.
	Glen Ellen Formation.
QTge	sand, gravel, mudstone, and minor interbedded tuffs.
	Merced Formation.
Tm	fine-grained sandstone and local minor coarse grained grit and tuff breccia, poorly indurated.

	Huichica Formation.
QTh	sand, gravel, silt, clay and locally interbedded tuffs.
	Petaluma Formation.
Tp	undivided.
Tps	claystone, siltstone, mudstone, tuff, with sandstone and conglomerate crossbeds.
Tpc	claystone.

Sonoma Volcanic Group.

(Not necessarily in correct stratigraphic sequence.)

Tsu	undivided; K-Ar age 11.8 million years in Burdell Mtn. area.
Tsr	rhyolite lava flows; locally contains intercalated tuff.
Tsrp	perlitic rhyolite; flows, plugs.
Tsri	rhyolite; plugs and dikes.
Tsrs	rhyolite; soda flows.
Tsrb	rhyolite breccia.
Tsa	andesitic to basaltic lava flows.
Tsft	tuff; interlayered with basaltic or andesitic flows.
Tsfd	andesite and basalt flows; thinly interlayered with diatomite and unconsolidated fine-grained sediments.

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GEOLOGY
SPECIAL REPORT 120 PLATE 3B

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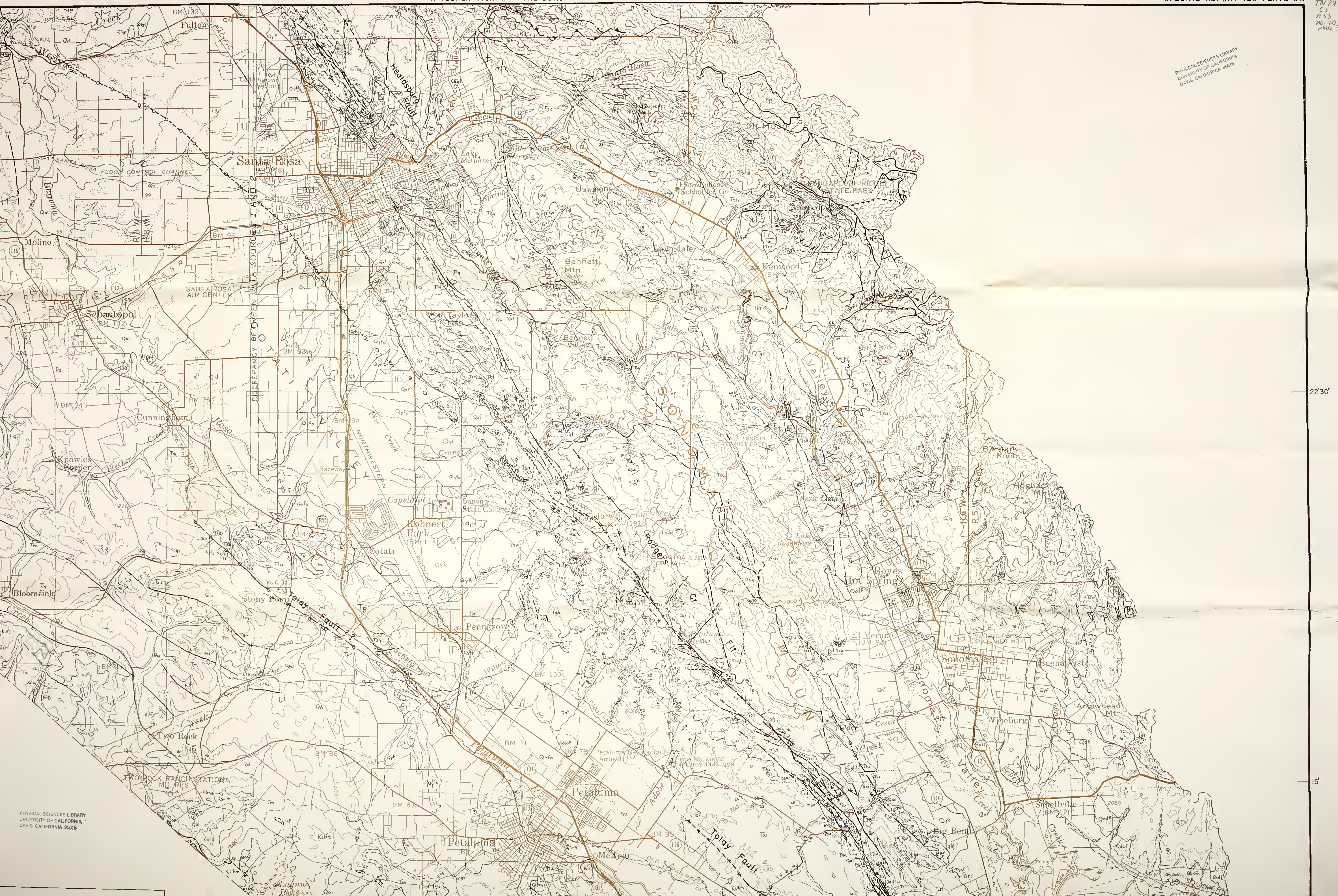

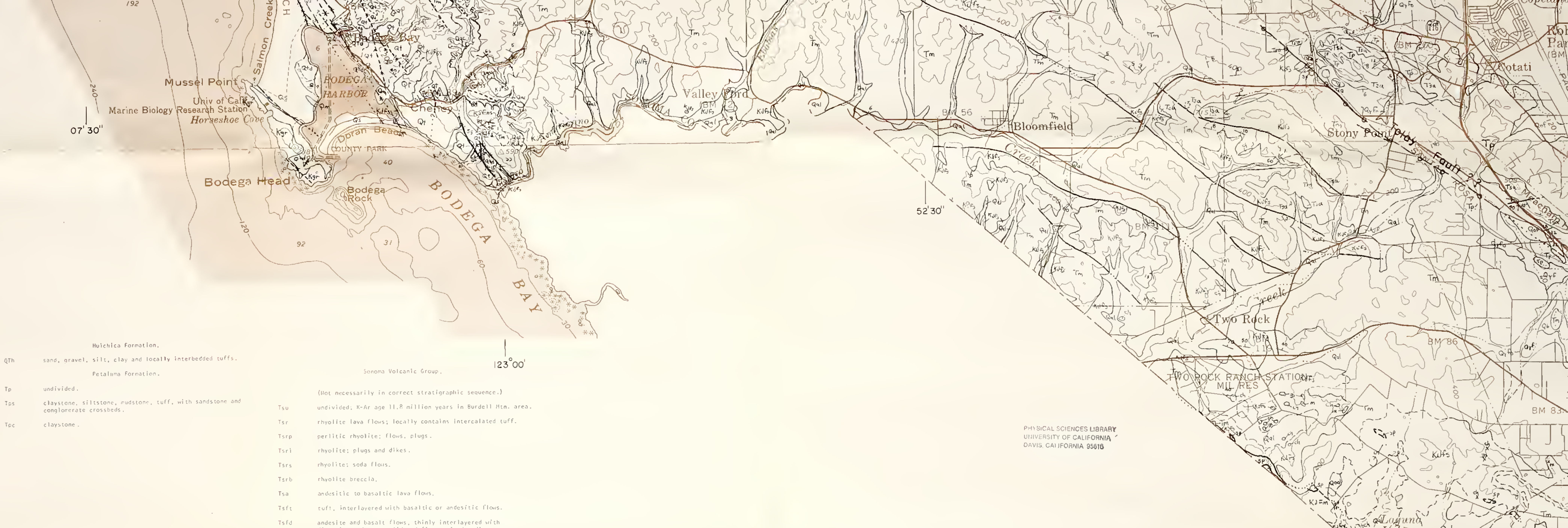

CENOZOIC

QUATERNARY

PLEISTOCENE-HOLOCENE

Qyfo	fluvial deposits at the outer edge of alluvial fans (Qyf), forms levees between basin deposits (Qb); characterized by fine, but variable, grain size; composed mainly of fine sand, silt, and silty clay.
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Qb	interfluvial marsh-like basin deposits; mainly poorly sorted dark clay and silty clay, both rich in organic matter.
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Qs	beach and dune sand.
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Qtd	marine terrace deposits; silt, sand, gravel.
Qt	stream terrace deposits; sand, silt and gravel; along the coast, undifferentiated marine terrace deposits and surfaces.
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Qg	poorly bedded gravel deposits.

PLIO-PLEISTOCENE

Glen Ellen Formation.

QTge	sand, gravel, mudstone, and minor interbedded tuffs.

Huichica Formation.

QTh	sand, gravel, silt, clay and locally interbedded tuffs.

TERTIARY

PLIOCENE

Merced Formation.

Tm	fine-grained sandstone and local minor coarse grained grit and tuff breccia, poorly indurated.

Petaluma Formation.

Tp	undivided.
Tps	claystone, siltstone, mudstone, tuff, with sandstone and conglomerate crossbeds.
Tpc	claystone.

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(Not necessarily in correct stratigraphic sequence.)

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Tsrp	perlitic rhyolite; flows, plugs.
Tsri	rhyolite; plugs and dikes.
Tsrs	rhyolite; soda flows.
Tsrb	rhyolite breccia.
Tsa	andesitic to basaltic lava flows.
Tsft	tuft, interlayered with basaltic or andesitic flows.
Tsfd	andesite and basalt flows, thinly interlayered with diatomite and unconsolidated fine-grained sediments.
Tst	pumicitic ash-flow tuff, locally welded or partly welded with intercalated bedded agglomeritic tuff, andesitic or basaltic lava flows, tuff breccia, bedded tuff, and pumicitic tuff.
Tswt	welded ash-flow tuff, subordinate unwelded or partly welded ash-flow tuff.
Tsag	agglomerate; with volcanic breccia, tuff breccia.
Tslt	tuff breccia; intercalated agglomerate, tuff.
Tss	sedimentary deposits; unconsolidated interbedded and intertonguing tuffaceous sand, silt, volcanic gravel, bedded tuff, clay, diatomite
Tsm	well bedded sandstone and mudstone near Fort Ross.

MIOCENE

Neroly ? Sandstone.

Tn	coarse-grained bluish-gray sandstone with minor tuffaceous sandstone, shale, and pebbly sandstone.
Ts	calcareous medium- and fine-grained sandstone and siltstone with local barnacle and mollusc fragments; and fossiliferous very coarse-grained pebbly sandstone.

MESOZOIC

JURASSIC-CRETACEOUS

Franciscan Assemblage

(Not necessarily in correct stratigraphic sequence.)

KJfss	predominantly graywacke-type sandstone and shale with minor greenstone, conglomerate, chert, and limestone. Rock pervasively shattered and commonly veined with laumontite. Sandstone massive and well-bedded to locally thin-bedded and flysch-like, and contains 5 to 25 percent detrital potassium feldspar.
KJfm	chiefly metagraywacke with slight to pronounced metamorphic fabric and minor metagreenstone and metachert; contains blueschist minerals, including glaucophane, lawsonite, and jadeitic pyroxene. Metagraywacke contains no detrital potassium feldspar.
KJfs	sheared shale and sandstone that contains generally resistant masses of chert, "high grade" metamorphic rock, variable shattered sandstone and greenstone, metagreenstone, and generally less resistant serpentinite (see below for lithologies and map symbols); masses range in length from less than one foot to greater than 5 miles, and constitute a variable, generally unknown proportion of the unit. K-feldspar generally absent. Parts of unit correspond to melange described by Hsu (1969).
ss	massive sandstone.
sp	serpentinite, including relatively fresh ultramafic masses. Occurs as lenses, sheets, and irregularly shaped masses, largely within and along boundaries of KJfs.
sc	silica-carbonate rock.
ch	chert, including metachert.
gs	greenstone, including pillow lava, tuff, minor intrusive varieties, and minor fossiliferous limestone, and metagreenstone ranging from rock containing incipient blueschist minerals to completely reconstituted blueschist. Masses range to longer than 5 miles.
gwy	graywacke-type sandstone, containing 0 to 5 percent detrital potassium feldspar, and some metagraywacke. Probably occurs in masses ranging to at least several miles long; map distribution largely unknown.
m, ♦	"high grade" metamorphic rock, chiefly gneissic, including glaucophane schist, eclogite, and amphibolite, most occurring in blocks less than 100 feet long.
mgs	ranges from greenstone with patchy occurrence of blue amphiboles to schistose rock containing well developed glaucophane and lawsonite. occurs in KJfm largely as the former, in KJfs largely as the latter in discrete masses as long as 1 mile.
mch	metachert; fine-grained banded chert with bands or layers defined by colors indicating the presence of blue amphibole; occurs as small discrete masses in KJfs.

Great Valley Sequence.

KJgv	undifferentiated rock; mainly well-bedded sandstone, shale and conglomerate.
KJgvs	sandstone with minor mudstone and shale.
KJgvc	conglomerate.
KJgvm	mudstone and siltstone, with sandstone.
Kgr	granitic rock.

JURASSIC

Jv	basalt; pillow lava and breccia.

SYMBOLS

Contact, solid line where well located, long dash where approximately located, short dash where inferred, dotted where concealed; query indicates additional uncertainty.

Fault; solid line where well located, long dash where approximately located, short dash where inferred, dotted where concealed; query indicates additional uncertainty. Arrow and number indicates direction and amount of dip in degrees. Whether or not the fault is active or poses any hazard to man is generally unknown. Only crosscutting faults are shown within KJfs, although most contacts therein probably are faults. Arrow and number indicate dip of fault plane.

Potentially active fault. These faults exhibit features indicative of geologically young (Quaternary) surface rupture. Therefore, they are considered to be capable of renewed surface movement.

Possibly active fault. These faults exhibit features suggestive (but not conclusive) of geologically young (Quaternary) surface rupture. Further studies are necessary to determine their potential activity.

Thrust fault; dashed where approximately located, queried where doubtful. Sawteeth on upper plate.

Anticline, dashed where approximately located.

Syncline; dashed where approximately located.

Overturned Syncline; dashed where approximately located.

Dip and strike of bedding; ball on dip bar indicates that top of beds is known from sedimentary structures:

50 45 inclined

⊗ horizontal

vertical

60 overturned

Dip and strike of flow banding

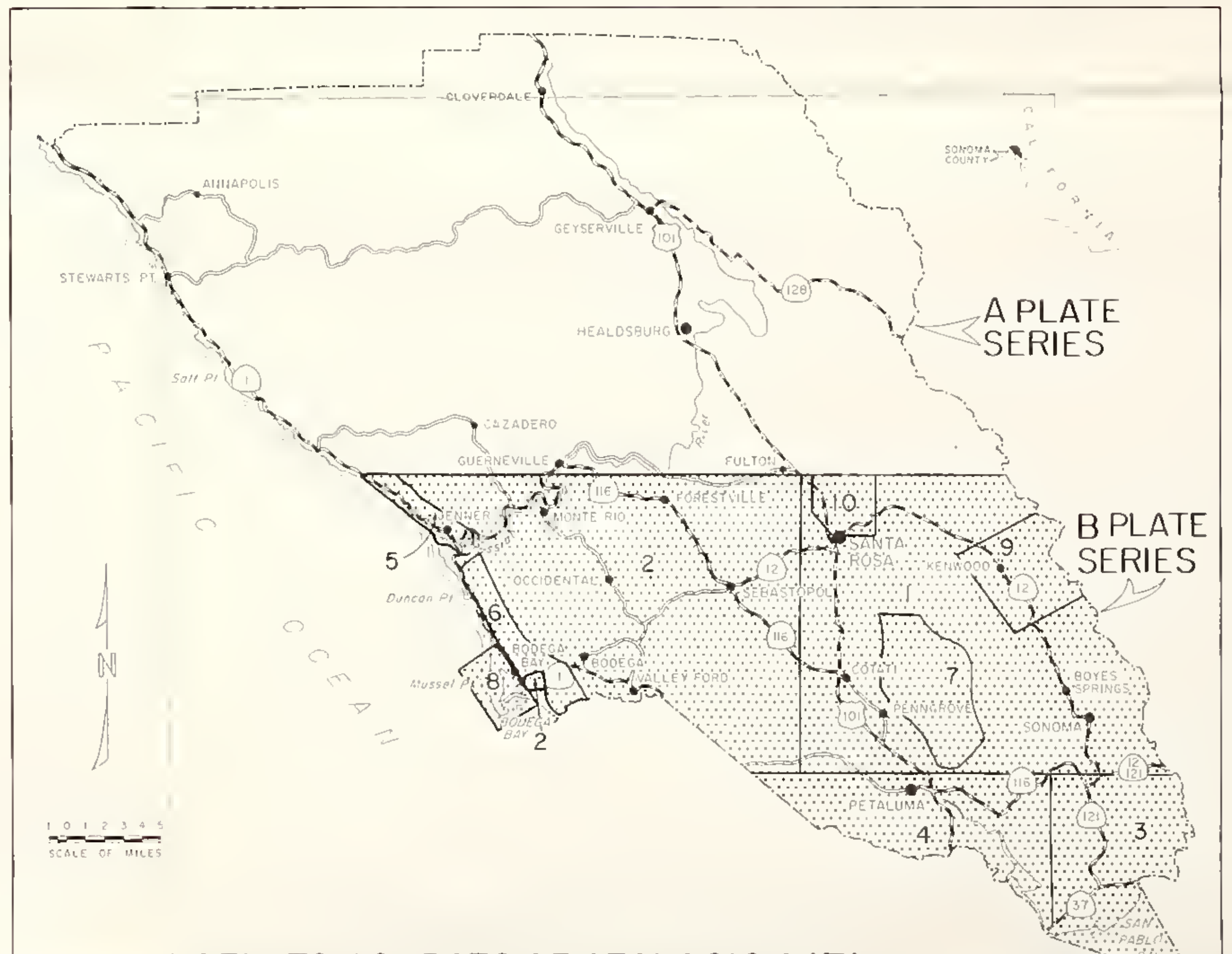
20 inclined

vertical

50 undulatory

→ flow lineation

Data is for the purpose of regional planning and for the assessment of studies that are required for land use and development planning. Geologic and soil reports are required for land development plans and designs.



INDEX TO SOURCES OF GEOLOGIC DATA

1. *Fox, K.F. Jr., et al, 1973; Jennings, C.W., 1973, modified by Armstrong, C.F., 1974.
2. *Blake, M.C. Jr., et al, 1971, modified by Armstrong, C.F., 1974.
3. *Sims, J.D., et al, 1973; Jennings, C.W., 1973, modified by Armstrong, C.F., 1974.
4. *Blake, M.C. Jr., et al, 1974; Jennings, C.W., 1973 modified by Armstrong, C.F., 1974.
5. Huffman, M.E., 1972, and Blake, M.C. Jr., et al, 1971.
6. Huffman, M.E., 1973, and Blake, M.C. Jr., et al, 1971.
7. Huffman, M.E., 1971, and Fox, K.F. Jr., et al, 1973.
8. Huffman, M.E., 1973, Blake, M.C. Jr., et al, 1971, Brown, R.D. Jr., and Wolfe, E.W., 1972, and Koenig, J.B., 1963.
9. Sickles, J.B., 1973, and Fox, K.F. Jr., et al, 1973.
10. Jennings, C.W., 1970; Active fault designations by R.D. Brown Jr., 1972 (Fox et al, 1973).

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*U.S. Geological Survey, Basic Data Contributions

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TOPOGRAPHIC BASE BY U.S.G.S
This map is an enlargement of a
1:125,000-scale published map.

GEOLOGIC MAP EXCLUSIVE OF LANDSLIDES - SOUTHERN SONOMA COUNTY

compiled by

Charles F. Armstrong

SCALE 1:62,500

CONTOUR INTERVAL 200 FEET

1980

l, 1973; Jennings, C.W., 1973, modified by
74.
al, 1971, modified by Armstrong, C.F., 1974.
973; Jennings, C.W., 1973, modified by
74.
al, 1974; Jennings, C.W., 1973 modified
1974.
and Blake, M.C. Jr., et al, 1971.
and Blake, M.C. Jr., et al, 1971.
and Fox, K.F. Jr., et al, 1973.
Blake, M.C. Jr., et al, 1971, Brown,
E.W., 1972, and Koenig, J.B., 1963.
and Fox, K.F. Jr., et al, 1973.
); Active fault designations by R.D. Brown
, 1973).

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IN COOPERATION WITH THE SONOMA COUNTY PLANNING DEPARTMENT

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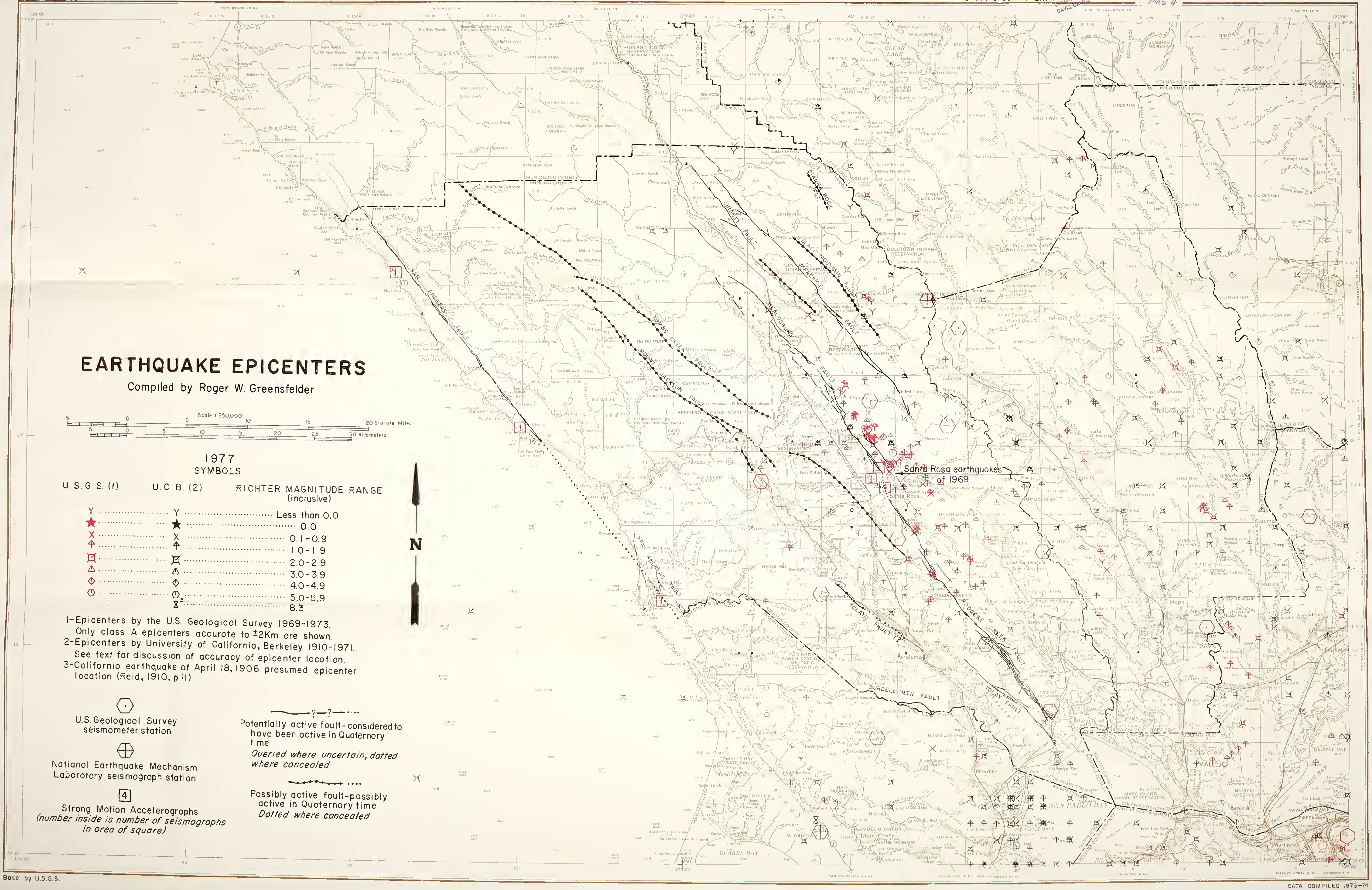
EPICENTERS
SPECIAL REPORT 120 PLATE 4



EARTHQUAKE EPICENTERS

Compiled by Roger W. Greensfelder

Scale 1:250,000
5 0 5 10 15 20 Statute Miles
5 0 5 10 15 20 25 30 Kilometers

1977
SYMBOLS

U.S.G.S. (1)	U.C.B. (2)	RICHTER MAGNITUDE RANGE (inclusive)
Y	Y	Less than 0.0
★	★	0.0
X	X	0.1-0.9
⍏	⍏	1.0-1.9
⌧	⌧	2.0-2.9
△	△	3.0-3.9
◇	◇	4.0-4.9
⦶	⦶	5.0-5.9
	X³	8.3

1-Epicenters by the U.S. Geological Survey 1969-1973. Only class A epicenters accurate to ±2Km are shown.
2-Epicenters by University of California, Berkeley 1910-1971. See text for discussion of accuracy of epicenter location.
3-California earthquake of April 18, 1906 presumed epicenter location (Reid, 1910, p.11)

⬡ U.S. Geological Survey seismometer station

⊕ National Earthquake Mechanism Laboratory seismograph station

[4] Strong Motion Accelerographs
(number inside is number of seismographs in area of square)

———?—?—···· Potentially active fault-considered to have been active in Quaternory time
Queried where uncertain, dotted where concealed

———····· Possibly active fault-possibly active in Quaternary time
Dotted where concealed

Base by U.S.G.S.

DATA COMPILED 1973-74

CALIFORNIA DIVISION OF MINES AND GEOLOGY
THOMAS E. GAY JR., STATE GEOLOGIST

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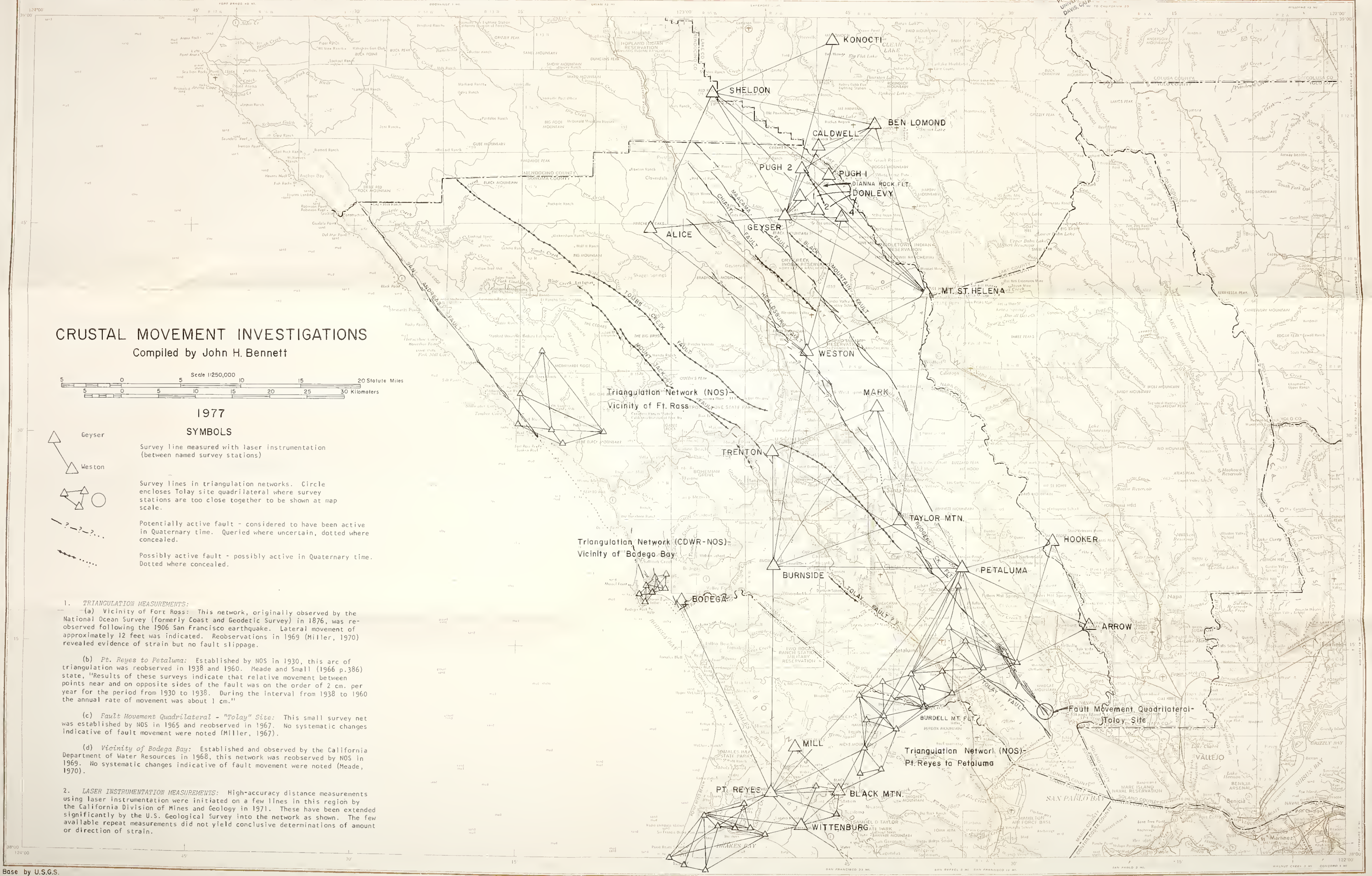
CRUSTAL MOVEMENT INVESTIGATIONS
SPECIAL REPORT 120 PLATE 5



CRUSTAL MOVEMENT INVESTIGATIONS

Compiled by John H. Bennett

Scale 1:250,000

5 0 5 10 15 20 Statute Miles

5 0 5 10 15 20 25 30 Kilometers

1977

SYMBOLS

Geyser — Weston: Survey line measured with laser instrumentation (between named survey stations)

Survey lines in triangulation networks. Circle encloses Tolay site quadrilateral where survey stations are too close together to be shown at map scale.

Potentially active fault - considered to have been active in Quaternary time. Queried where uncertain, dotted where concealed.

Possibly active fault - possibly active in Quaternary time. Dotted where concealed.

1. *TRIANGULATION MEASUREMENTS:*

(a) Vicinity of Fort Ross: This network, originally observed by the National Ocean Survey (formerly Coast and Geodetic Survey) in 1876, was reobserved following the 1906 San Francisco earthquake. Lateral movement of approximately 12 feet was indicated. Reobservations in 1969 (Miller, 1970) revealed evidence of strain but no fault slippage.

(b) *Pt. Reyes to Petaluma:* Established by NOS in 1930, this arc of triangulation was reobserved in 1938 and 1960. Meade and Small (1966 p.386) state, "Results of these surveys indicate that relative movement between points near and on opposite sides of the fault was on the order of 2 cm. per year for the period from 1930 to 1938. During the interval from 1938 to 1960 the annual rate of movement was about 1 cm."

(c) *Fault Movement Quadrilateral - "Tolay" Site:* This small survey net was established by NOS in 1965 and reobserved in 1967. No systematic changes indicative of fault movement were noted (Miller, 1967).

(d) *Vicinity of Bodega Bay:* Established and observed by the California Department of Water Resources in 1968, this network was reobserved by NOS in 1969. No systematic changes indicative of fault movement were noted (Meade, 1970).

2. *LASER INSTRUMENTATION MEASUREMENTS:* High-accuracy distance measurements using laser instrumentation were initiated on a few lines in this region by the California Division of Mines and Geology in 1971. These have been extended significantly by the U.S. Geological Survey into the network as shown. The few available repeat measurements did not yield conclusive determinations of amount or direction of strain.

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